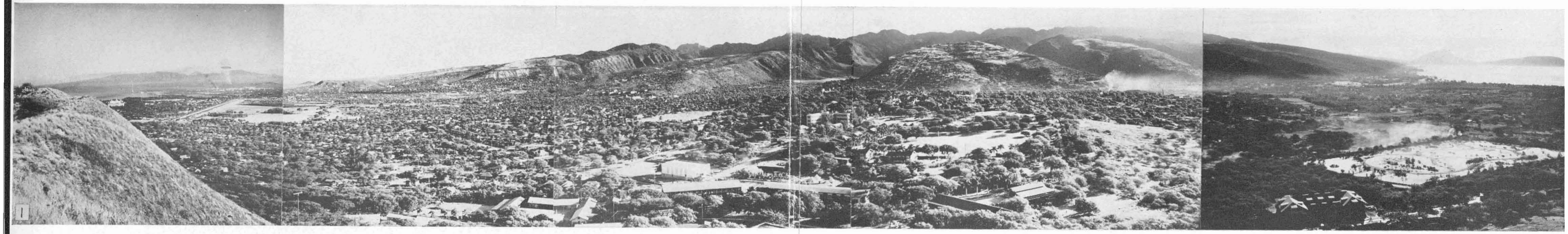
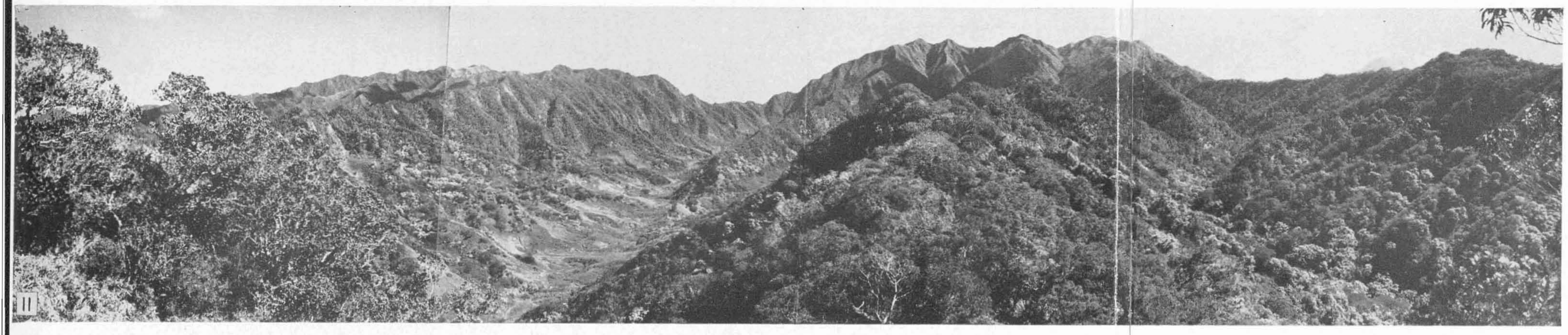
Geology and Ground-water Resources of the Honolulu-Pearl Harbor Area Oahu, Hawaii

CHESTER K. WENTWORTH

BOARD OF WATER SUPPLY
CITY AND COUNTY OF HONOLULU
HONOLULU, HAWAII
1951





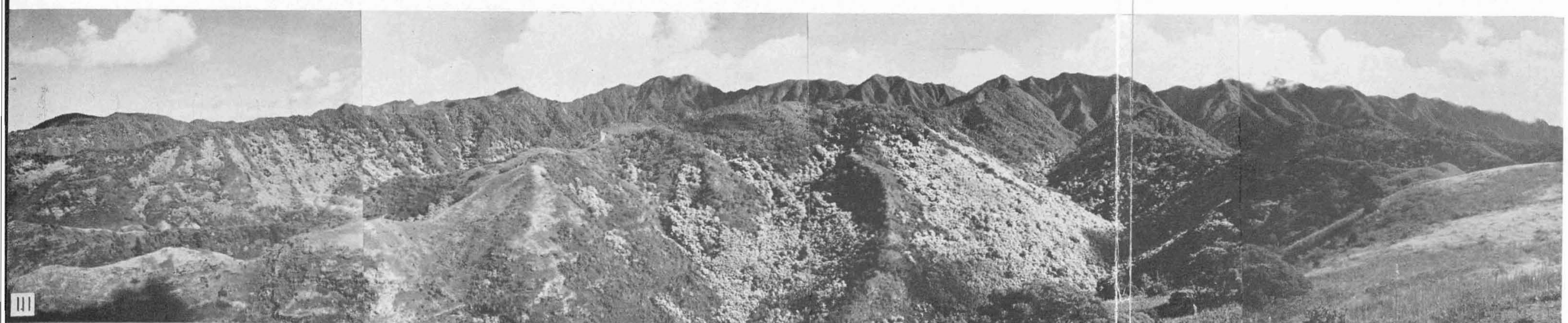


PLATE I. Panorama of southeastern Koolau Range from inland rim of Diamond Head. Central foreground is the low dome of Kaimuki; left foreground is coastal plain with Punchbowl and the Waianae Range in the distance. Right foreground is Waialae coastal plain, narrowing to zero and with Koko Head and Koko Crater in the distance. Beyond the foreground are flow-slope facets and intervening valleys with the dissected range crest forming the distant horizon.

PLATE II. Panorama of inland Koolau topography, from ridge peak between Moanalua Valley, left of center, and Manaiki, right. Moanalua Valley shows more open country and less forest in the inland bottom part than most other valleys. The peak in the center is just over 2,800 feet.

PLATE III. Panorama of Koolau Range from Waialaenui apex (1,357 feet), showing Waialaenui Valley, right foreground, east-facing west wall of Palolo Valley at left center, with Tantalus, Roundtop, Lanihuli, Konahuanui, and Olympus, in order from the left end to just left of center. Remaining high crestline is from Tantalus to about 1 mile east of Lanipo. The light patches of forest marking the side valleys consist of the kukui or candlenut tree, whose light-green foliage is emphasized by a red F filter.

PLATE IV. Panorama of Kapahulu facet and ridge, from Kalaepohaku, above St. Louis Heights. Extends from the peak Lanipo in the distance at the left, past the facet apexes of Waialaenui, left of quarry, and Maunalani Heights, right of quarry, to the Waialae coastal plain and Diamond Head. The dark ridge, foreground left of center, is the divide between Waiomao and Pukele branches of Palolo Valley. (April, 1938.)

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FOREWORD

When the early missionaries and other visitors to Hawaii first settled at Honolulu ("Fair Haven"), the choice of a site was based on sheltered anchorage and proximity to the Hawaiian village at Waikiki. No one at that time suspected the presence of the remarkable water supply which has permitted growth of the present metropolis. After use of water from various springs and from Nuuanu Stream, all successively inadequate, the existence of large supplies of artesian water was discovered, quite by accident, in 1879.

Development of the artesian water by rule-of-thumb methods went on rapidly. Logical understanding of its behavior has come very slowly. Soon after annexation of Hawaii to the United States in 1898 efforts were made to have surveys of water resources made by the U. S. Geological Survey. Surface-water studies were started in 1909, ground-water studies in 1919. As data were accumulated, various engineers such as G. K. Larrison, John McCombs, and J. F. Kunesh, among others, recognized and classified the forms of occurrence of ground water. Interpretation of the relationship of these to geologic formations was elaborated by W. O. Clark of the Hawaiian Sugar Planters' Association and Harold S. Palmer of the University of Hawaii. Mr. Clark reported on the geology of perched ground water in the Pahala area of Hawaii. Dr. Palmer made the first geologic reports on both the high-level and the artesian ground water of the Honolulu area. Before this, Carl B. Andrews, now professor emeritus of engineering of the University of Hawaii, made the first systematic explanation of the artesian and Ghyben-Herzberg condition at Honolulu, but his report, a thesis for presentation at Rose Polytechnic Institute in 1909, was not widely known.

Great impetus was given to systematic water development as a result of the completion of the geologic and ground-water survey of the island of Oahu by Harold T. Stearns of the U. S. Geological Survey in 1935. This was the first major result of the cooperative agreement between the U. S. Geological Survey and the Territorial Division of Hydrography for a geologic survey of the Territory.

When the latter survey was well advanced, the Board of Water Supply recognized that to outline adequately its future development of water for municipal supply, further geologic investigation under its own supervision would be required. Accordingly, Chester K. Wentworth, who had made various geologic studies both in Hawaii and on the United States mainland, was employed to continue the examination of rock structures and ground-water conditions in the Honolulu and adjacent Pearl Harbor watersheds. The present report is the result of his field studies and analyses of hydrologic data from 1934 to the present time.

The hydrologic part of the report testifies both to the remarkable features of the floating Ghyben-Herzberg lens, from which most of our water comes, and to the great advance in detail and methods of hydrologic analysis that has taken place in the past two or three decades. Such work is dependent on adequate records of draft, rainfall, and water levels, which, locally, are not available for years earlier than 1925.

As with earlier reports, the present one offers some answers, shows much advance in logical understanding, and also poses many new questions. This program has required field and survey work, the analysis of a large body of data, and a considerable amount of original thinking in a more-or-less uncharted field. I appreciate very much Dr. Wentworth's sincerity and painstaking study of this subject, and, on behalf of the Board of Water Supply, I am pleased to offer this report as a substantial step toward operational understanding of the Honolulu ground-water supply.

FREDERICK OHRT
Manager and Chief Engineer
Honolulu Board of Water Supply

PREFACE

This report summarizes findings in the investigation, commenced in 1934, of the geology and water resources of the Honolulu area. The general field study of the geology of the Honolulu leeward slope of Oahu was completed in 1942, and a somewhat less complete study of the Pearl Harbor area has been reported more recently. In addition to the areal field studies, much attention has been given to analysis of the hydrologic data in an effort to further quantitative understanding of the artesian and basal water systems.

Most of the data secured in these studies are contained in manuscript reports, field and laboratory notebooks, and computation books in the files of the Board of Water Supply. A few brief papers have been published in technical journals, but the present report is the first attempt to cover the whole subject in printed form. Of necessity it is only an outline summary; an effort has been made to give the chief conclusions, to state methods, and, particularly, to indicate the stage of understanding attained and suggested lines of further investigation.

C. K. W.
Honolulu, Hawaii
April, 1951

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INTRODUCTION

LOCATION AND AREA

This report deals with about half of the leeward or southwest slope of the Koolau Range of Oahu including the adjacent Honolulu and Pearl Harbor coastal plain areas (fig. 1). The entire region, extending some 22 miles along the southern shore from east of Diamond Head to Barbers Point, is by far the largest producer of ground water in the Territory of Hawaii. The explanation is found in its geologic history and structure. The total extent of the drainage area is about 192 square miles, or almost a third of the island of Oahu. The eastern boundary has been taken as the axis of Wailupe Valley; the inland boundary is the crest of the Koolau Range; the northern limit is approximately the drainage divide across the Schofield Saddle; the western boundary is strictly the sea-level contact, the position of which is not accurately known, of Koolau lavas on the Waianae dome; and the line then follows the south coast back to the mouth of Wailupe Valley.

PURPOSE OF STUDY

Following the discovery of artesian water in 1879 and the annexation of the Territory of Hawaii in 1898, systematic studies of surface-water and artesian-water supplies were begun by the U. S. Geological Survey in 1909. It was recognized that geologic investigations were essential to understanding and full development of the ground-water resources, and a study of high-level ground water in the Honolulu area was completed by Palmer in 1921. Palmer later completed and published a study of the artesian system (1927). On the completion of the revised topographic map of Oahu in 1930, the U. S. Geological Survey commenced the systematic geologic mapping of Oahu and the compilation of ground-water data which led to a report completed in 1935 (Stearns and Vaksvik, 1935). Importance to the city of Honolulu of its ground-water supply led this office in 1934 to undertake the more detailed survey of the Honolulu and adjacent Pearl Harbor area which is reported herein.

This work was aimed at determining the location and amount of available high-level water in the Honolulu area and the extent and nature of the rocks of the intake area as well as of the caprock responsible for the artesian condition. It was also desired to develop a more complete explanation of the hydrology of the artesian-water body with its several so-called isopiestic areas and of the structural and other conditions responsible for the observed differences in head and amounts of water. On completion of the field studies it became evident that amounts of water available from high-level sources will be relatively small. It has therefore become increasingly apparent that the major hydrologic problem of the Honolulu water supply is that of rational, long-term use and development of the basal water, whether in the Honolulu area proper or in the adjacent Pearl Harbor area.

Moreover, with increased demands for water and the need for emergency development during the war period, it appears that development, use, and management of the water supply of southern Oahu is a unit problem. Only temporary and local solutions result from operations that fail to take account of the composite needs of the whole area. Such interdependence is indicated both in the lagging relationship of adjacent ground-water bodies and in the similar responses of the juxtaposed agricultural, military, and municipal use. The present study is offered as a contribution on the geologic and hydrologic aspects of the continuing problem thus posed.

ACKNOWLEDGEMENTS

In course of this study, the writer has been assisted in the most cordial manner by many engineers, officials, and students of geology and water supply. Dr. Harold S. Palmer of the University of Hawaii, Max H. Carson, Dr. Harold T. Stearns, and Dr. G. A. Macdonald of the U. S. Geological Survey, and W. O. Clark, former geologist of the Hawaiian Sugar Planters' Association, have been foremost among those who have repeatedly joined in field conferences, made reports and data available, and assisted in many other ways.

Special gratitude is due successive geologic assistants—R. G. Sohlberg, Austin E. Jones, and Horace Winchell—for their aid in carrying on arduous field work and in contributing to discussions and various special investigations summarized herein. Equally warm thanks are due to a succession of trail aides who took a very vital part in the field work in the rugged mountain section. It is difficult to overstate the fidelity and hard work by which they carried on operations whose purpose may not always have been clear, or the credit due them for the safe conduct of many months of work involving considerable aggregate hazard.

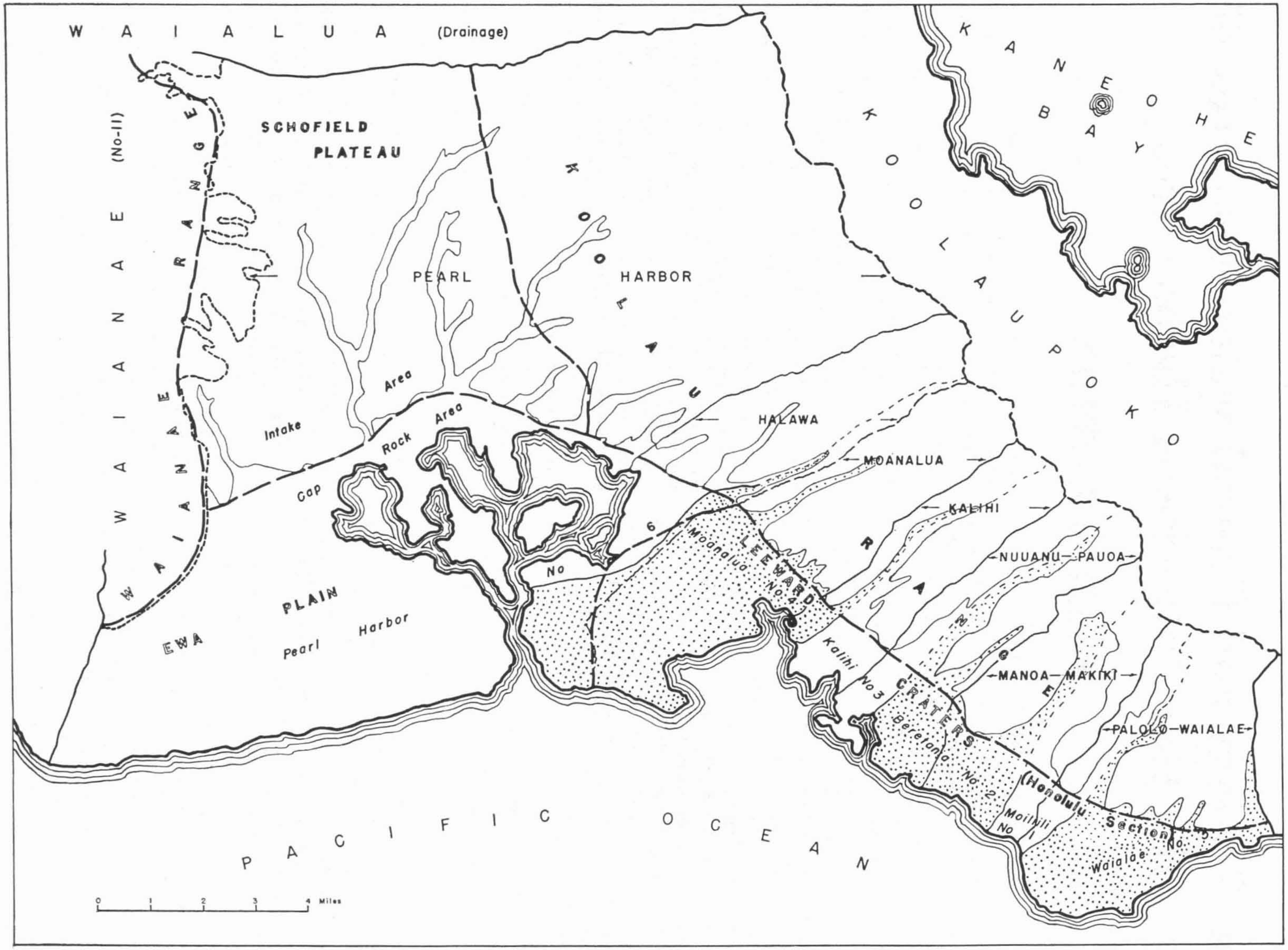

FIGURE 1. Sketch map of the Honolulu–Pearl Harbor area, showing intake area (blank, inland from heavy line) and caprock area (alternating blank and stippled) along coast. Six drainage basins are discriminated in the inland area by names and arrows in the Honolulu portion. Isopiestic basal areas 1 to 5 are shown by names and alternating stipple and blank pattern, with area number 6 (Pearl Harbor) on the left. The valley bottom tongues (stippled) in the Honolulu section are known to be ground-water barriers, those in the Pearl Harbor section (not stippled) are apparently not effective ground-water barriers.

Plans for the investigation were laid by Dr. Herbert E. Gregory, then a member of the Board of Water Supply, and he offered suggestions and comments at various times during the earlier part of the work. Simes T. Hoyt, also long a member of the Board, has taken a keen interest in various geologic and hydrologic studies and has offered extremely valuable suggestions throughout the entire period. After completion of most of the field work, Ellwood Bartz rendered material assistance in analyzing data, organizing measurements and tests, and in discussions relating to the report. Since 1947, Dan A. Davis of the U. S. Geological Survey has collaborated in various ways on hydrologic problems and has made valuable suggestions as to procedure. Both the writer and the Board of Water Supply are greatly indebted to Juliette Wentworth for discriminating assistance in editing and seeing this report through the press.

During the past 10 years, Dr. G. A. Macdonald has been most helpful in many ways. He has joined with the author in a number of studies and has taken part repeatedly in discussions on geologic findings or interpretations and their hydrologic implications. His competent knowledge of geology and the local problems and his sound judgment have been of the greatest aid before and during the preparation of this summary.

More than to anyone else, the author is grateful to Frederick Ohrt, Chief Engineer of the Board of Water Supply, for the assignment and constant aid and support which have made completion of the work possible. Combining an unceasing alertness to the practical needs of the water department with broad faith in the ultimate value of technical understanding, Mr. Ohrt has provided not only support in essential particulars but also, at various points, the challenging criticism which is equally needed. The extent of his over-all contribution cannot be overemphasized.

GEOGRAPHY

GEOMORPHIC DIVISIONS

Oahu has been divided into 10 geomorphic provinces on the basis of features resulting from contrasting rock structures and geologic history (Wentworth, 1939a). The relationship of the Honolulu and Pearl Harbor areas here discussed to the geomorphic divisions is shown in figure 1. The larger part of the intake area is contained in the Koolau Range province and consists of the maturely dissected, extremely rugged ridges and valleys of the leeward slope. Included within this province are the floors of filled valleys which are in reality extensions of the coastal plain cap.

The Honolulu coastal plain lies in the leeward craters province, which also includes the Salt Lake area as far west as Pearl Harbor. This designation emphasizes the importance of the secondary craters in the growth of the coastal plain. The central and western part of the Pearl Harbor area constitutes the Ewa Plain, a part of which has long been known as the Ewa Coral Plain. Inland from this province is the Schofield Plateau, made up of Koolau lava flows that are little dissected except for the trench-like valleys of the main streams that issue from the rugged mountain province.

DRAINAGE

This section of Oahu is drained by about 25 streams which follow courses consequent to the slope of the range and to that of the Schofield Plateau (fig. 2). In the eastern or Honolulu part of the area, the streams are 4 to 6 miles in length and their courses lie mostly within the mountainous part of the range. The streams rise in one or more rills which drain the steep valley heads from the crest at 2,000 to 3,000 feet in elevation. The middle portions of these streams flow in narrow, steep-sided valleys, 1,000 to 1,500 feet deep. Some of the valleys widen in the lower portion to round bottoms a half mile or more wide, especially where they are filled by several hundred feet of sediments and late lava flows. The lower courses of these streams lie on the coastal plain and have patterns complicated by various local derangements, including diversions by late cones and lava flows.

Most conspicuous, the drainage of at least 10 of the major streams of the western portion is combined in the Pearl Harbor outlet. The eastern pair of these streams, North and South Halawa, flow in two distinct stream valleys in the mountain section, but the channels are merged on the coastal plain before they enter the eastern arm of Pearl Harbor. The westernmost of the major streams—Waiawa, Kipapa, and Waikakalaua—in their upper courses flow in a southwesterly direction consequent to the main leeward slope of the range, but in their lower courses they follow increasingly broad curves swinging to the south or even east of south on the southern slope of the Schofield Saddle. These streams follow the same consequent courses as did the later Koolau lava flows on the growing Koolau dome, as obstructed by the Waianae Range.

A western branch of the Waipahu (Waikele) Stream drains off the Waianae slope from near Kolekole Pass, and the whole pattern of the Honouliuli Stream is developed in the depression between the Koolau and Waianae domes.

TOPOGRAPHY

The area covered in this report stretches from the Koolau Range crest to the southern coast of Oahu. The stream-channel distance at the Wailupe end, east of Diamond Head, is less than 4 miles; through the Honolulu section it is 5 to 6 miles. At the north and west end, the channels of the longest streams are 15 miles in length to the mouth at Pearl Harbor and 20 miles to the true coast at the Pearl Harbor entrance (plates I, II, III).

The crest elevation of the Koolau Range is generally from 2,500 to 3,000 feet, with the maximum at 3,150 feet and with a few gaps at valley heads that are below 2,000 feet. On the windward side, bordering the present district, is the cliff or pali that slopes at 50 to 80 degrees to elevations below 1,000 feet. On the leeward side of the crest the alternating valleys and dividing ridges extend toward the south coast. The heads of valleys average somewhat less than a mile in width and are blunt and steep-sloped. A few have but a single head branch but others have several shallow, palmately arranged branches whose basins together approximate an amphitheater. The stream channels commonly fall 1,000 to 1,500 feet in the first mile of the valley.

The inter-valley ridges, as well as the short branch ridges, are generally steep-sided and narrow. Their crests rise and fall within a range of 100 to 300 feet, and the higher points taken together indicate the original height of the volcanic dome within a few hundred feet (Wentworth and Winchell, 1947, p. 54).

The ridges join the broader flow-slope facets at elevations of 1,600 to 1,000 feet, and the latter extend seaward to the margin of the exposed range at 100 feet or less above sea level (plate IV). The valley bottoms assume less steep grades at elevations of 1,000 feet, more or less, and thence the channels are commonly strongly curved from side to side. These curves are probably not true meanders, nor necessarily entrenched meanders, but have been largely induced by the alternate invasion of detrital fans from the side walls. At the outer ends of the bends, the streams usually cut against bedrock at the foot of a slope which carries little or no detritus. The inner edge of the curve often exposes old gravel lying on weathered

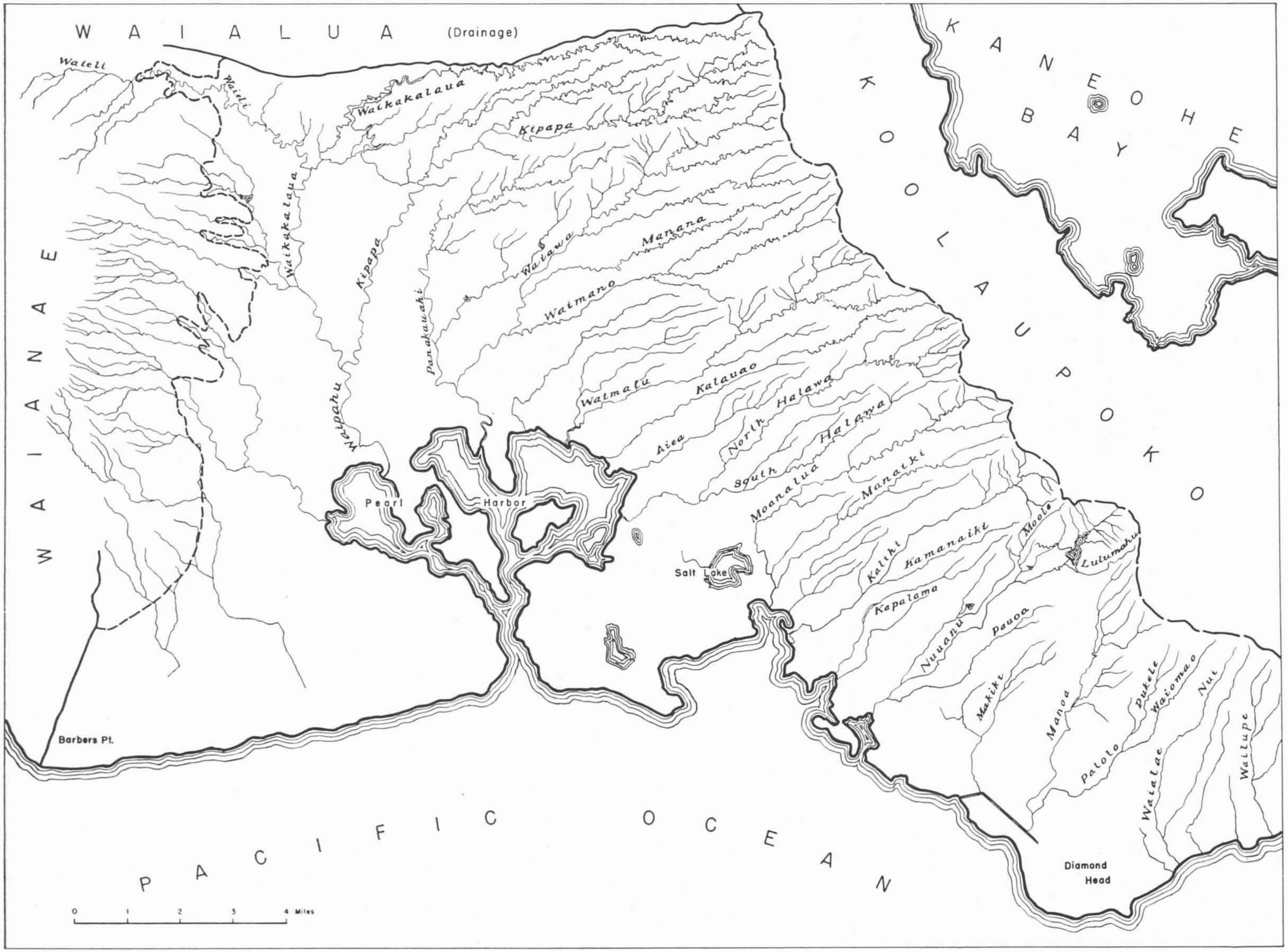

FIGURE 2. Drainage map of Honolulu–Pearl Harbor area showing the names of the principal streams.

bedrock of a spur which may extend as much as 1,000 feet out from the line of the opposite valley wall.

Except for the crests of the ridges, along which some sort of trail can be cut, and the stream channels, the entire mountain area is made up of steep slopes, with many waterfalls and cliffs. The whole is covered with dense vegetation and much of the exposed surface of rock is deeply weathered. All parts can be reached, if need be, without ropes, but at great expense of labor and need for caution. Systematic use of rope, handled by an assistant, has proved to be most convenient.

The coastal plain area of the Honolulu and Pearl Harbor sectors ranges from sea level to elevations that are mostly not above 50 feet except where the plain is surmounted by tuff cones, such as Diamond Head or those of the Salt Lake group, or where there are remnants of a terrace graded to a higher stand of the sea. Such terraces lie west of Kalihi; the chief area of higher ground east of Kalihi is the broad lava dome of Kaimuki, about 2 miles in diameter and reaching to about 302 feet at the crater apex.

Diamond Head has a circular rim, about a mile in diameter, generally reaching to about 400 feet and with the highest peak, at the southwest, standing at 760 feet. Punchbowl is slightly smaller, with the rim peak, also at the leeward or southwest, at 498 feet. The central bowl of Punchbowl is shallower and is heavily mantled by Tantalus cinders. The rim of Salt Lake Crater is somewhat lower, and the central bowl reaches just below sea level. Aliamanu, next west of Salt Lake, is represented by a central bowl and two peaks formed from the erupted ash altered to tuff. Makalapa, third vent of this group, is marked by a small oval bowl which was once used by the plantations as a storage lake and which has lately been largely filled during the wartime development of the Pearl Harbor area.

At the mouths of most of the major valleys, the coastal plain merges with a valley flat. These valley flats are constructional, made up chiefly of detritus; but in some of them lava flows and ash beds from secondary vents make up part of the section. The flats are the tops of the valley fill which ranges from as little as 100 to 150 feet in depth to as much as 1,000 feet where the bedrock valley profile lies as much as 1,000 feet below present sea level. The valley flats range in width from a few hundred feet in the lesser of the major valleys to 2 miles or more, and the flats extend inland from a few hundred yards to 3 or 4 miles. The elevation of the valley flat at the mouth and of the adjacent coastal plain depends on the structure and on the presence or absence of terraces or late lava flows, but is generally from 50 to 150 feet. Some of the valley floors, as especially Nuuanu Valley, are convex in cross profile, with the middle higher than the sides owing to fill by lava flows and the development of stream trenches on the two sides.

The end of the valley flat generally coincides with the end of deep fill, and the valley bottom thence generally becomes narrow and somewhat winding with only slight flats on the insides of bends in accordance with contemporary stream regimen.

The flow-slope facets in the Honolulu area are of triangular form and have areas of less than a square mile each. Parts of them are little eroded, and, as seen from a distance, the unity of their sloping surface is very distinct. Some are eroded near the lower edge or have shallow valleys developed near one side. Farther west, in the section northeast of Pearl Harbor, the facets are slightly more irregular and less distinct, partly because the adjacent valley walls are less sharply cut against them. Beyond this section, where the mountainous portion is bordered by the low slopes and broad surface of the Schofield Saddle, the facets are but the upper end of broad areas of original lava flow surfaces that stretch between the stream valleys 5 and 6 miles from the Pearl Harbor shore. In places this lava surface slopes no more than 100 feet to the mile and the slope does not generally exceed 200 feet to the mile. It represents for Hawaiian lava flows nearly the minimum slope on which they move effectively, probably after considerable thickening and pooling.

CLIMATE, SOILS, AND SETTLEMENT

Chief element of the climate with which we are here concerned is rainfall, which will be discussed in detail in another section. The area of this report experiences temperatures that range from 55 to 90 degrees Fahrenheit at sea level and, so far as known, about 6 to 8 degrees lower at the summit of the range. The soils have been described by Foster (1939, pp. 57–81), and it is sufficient here to say that at low elevations the soils are of the sublateritic type, higher in iron and lower in silica than the parent rock. On the other hand, with increase of elevation and growth of the forest cover, which becomes general at 1,000 to 1,500 feet according to exposure, the soils become lower in iron and retain more of the silica. At the higher elevations there is a greater preservation of humus material, and in a few small areas that have been little eroded over a long time there are peat layers and the formation of thin bands of ceramic clay with relatively low iron content and fairly high alumina and silica percentage (Wentworth, Wells, and Allen, 1940). It is sufficient here to note that the soils and subsoils of Oahu, of whatever character, taken as a thick body of cover, are of relatively low permeability as compared to the lava flows from which they were formed. The lava flow formations are the main aquifers. Wherever weathered detritus accumulates, as in the lower valley bottoms and to a lesser extent on the flow-slope facets, the compacting of the lower layers causes them to become rather effective caps or water barriers. Notwithstanding, in the mountainous area, despite the general soil cover and extensive weathering, there is evidently enough movement of the soil mantle and there are enough thin portions so that large amounts of rainfall pass through and do enter the deeper ground-water circulation.

In the lowland parts of the Honolulu area, where the coastal caprock diverts the rainfall from the main water body, the land is thickly settled and there is also a growing expansion of population into the narrow valley bottoms and on the flow-slope facets. It is a fortunate circumstance that the areas which by elevation, slope, and soil conditions are attractive for settlement are chiefly not the major intake areas for the basal water supply, though certain marginal areas will be increasingly at issue in this regard.

Among the native Hawaiians, land was used in narrow units extending from the crest of the mountains to the sea; the family holding such a unit thus had access to the products and the environment of the forests, the lowlands, and the sea. Under the present urban trend in Honolulu, as well as under the agricultural pattern of the larger part of the Territory, the tendency is to develop a land pattern that trends parallel to the coast, with the forest and rainfall-catchment area separated from successive agricultural or urban belts that depend usually on a suitable soil and lesser elevation, ruggedness, and rainfall. Because of the tendency for land to be transferred in legal units that still are largely radial in extent, a long period of experiment and considerable organized planning will be needed before a valid adjustment of modern land use to the natural and permanent conditions is achieved.

In the Pearl Harbor area, a similar line of demarcation exists between the portions that are settled or tilled and those that are of use almost exclusively as water-catchment areas, except that absolute elevations differ. Sugar cane is grown on the Koolau surfaces, both of the smaller facets in the eastern section and also of the larger areas that slope down from the Schofield divide. Sugar cane also grows surrounding Pearl Harbor on large areas that are part of the coastal plain or of tuff crater slopes and also on the lower valley bottoms or terraces adjacent to the coastal plain. This is true despite the reduction in area of sugar plantations through encroachment of military areas and establishments, a part of which will be permanent. Of the total of 58 square miles of coastal plain and intermediate slopes of the Pearl Harbor area considered as not effective intake area, more than one half is still in sugar cane.

Above the sugar cane fields in the Schofield Saddle area, pineapples are grown, not absolutely because of elevation limits on sugar cane growth, but because of the lack of cheap irrigation water above the level at which the Waiahole system delivers water by tunnel from the windward side of the Koolau Range. Under these practical conditions the line is sharp at elevations ranging from 750 feet on the east side to 640 feet on the west side where the Waiahole Ditch delivers Koolaupoko water to the margin of the Waianae Range.

Honolulu lies wholly within the area here discussed; Aiea, Pearl City, Waipahu, and Ewa are the principal civil towns. Settlements surrounding Pearl Harbor during World War II housed large numbers of both military personnel and civilian workers.

GEOLOGY

GENERAL GEOLOGY OF THE KOOLAU RANGE

The eastern part and considerably more than half the island of Oahu is made up of the Koolau volcanic dome[1] which was built around a rift line more than 30 miles in length. This dome is composed of thin basaltic lava flows with very minute proportions of ash beds. Except locally in the rift zone, there are only negligible amounts of intrusive rock. The portion above sea level is younger than the Waianae dome, which forms the smaller and western part of the island. The Koolau lavas overlap the eastern slope of the Waianae Range to nearly 1,000 feet above sea level and form a broad saddle of low slope between the steeper parts of the two domes (fig. 3).

The rift zone of the Koolau dome is marked by a dike complex in which the normal thin lava flows are cut by numerous parallel or subparallel dikes. The dikes in places reach a concentration of upward of 100 to the mile, but except in limited bands do not constitute the entire mass.

The Koolau dome has been deeply dissected to a mature topography with a relief commonly reaching 500 to 1,000 feet. The southeastern half of its windward or northeastern slope has been more markedly eroded so that its original form is not indicated by concordant ridges,

[1]These masses are called volcanic shields by some volcanologists; in this report it seems best to adhere to the term "dome," which is better understood locally.

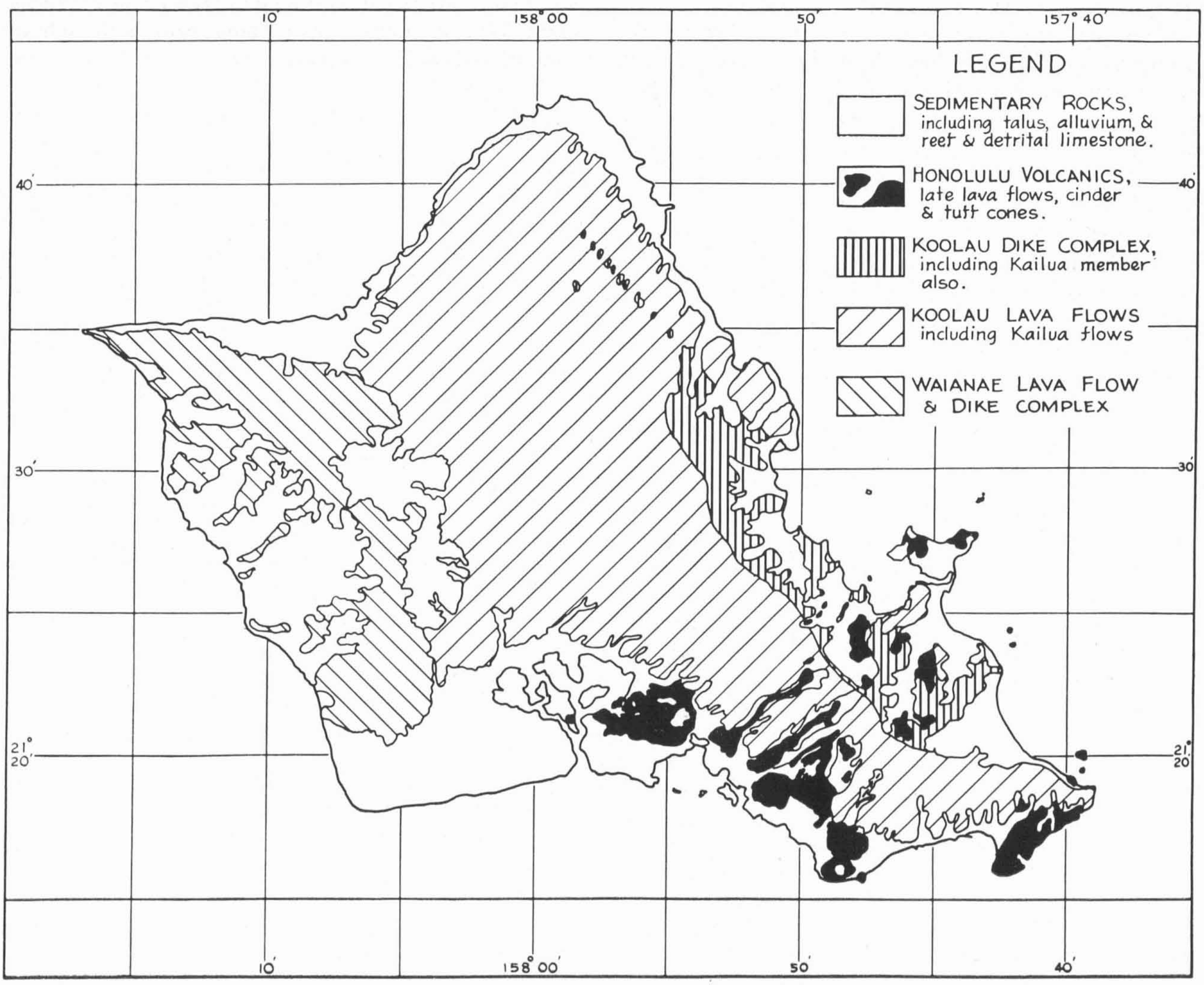

FIGURE 3. Generalized geologic map of Oahu.

but the general form of the original volcanic dome of the remainder is fairly evident (fig. 4) (Wentworth and Winchell, 1947).

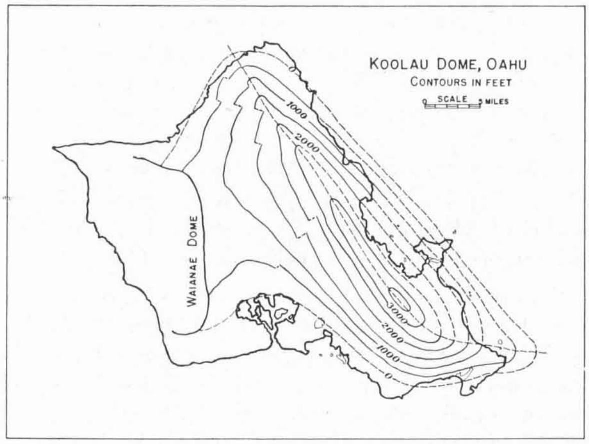

FIGURE 4. Map showing probable original form of the Koolau dome. Contours are drawn as envelopes to the most protruding contours of the existing topography, with an estimate for erosion. No evidence is found for widening on the northwest side. The narrow, elongate character is shown by the form of surviving topography and by the dominance of the dike complex as a vent system.

The present dissected mass is known as the Koolau Range; its southeastern third is marked by the secondary ash and tuff cones and valley-filling lava flows of the Honolulu volcanic series (Stearns and Vaksvik, 1935, pp. 98–165). Rocks of this series were erupted from about 30 different vents (fig. 6) and consist chiefly of ultrabasic basalts and corresponding glassy ash and cinder beds and of the palagonitic tuffs altered from the finer ash deposits (Winchell, 1947).

These rocks were placed during volcanic episodes that appear to have extended through much of the later Pleistocene but were separated from the main Koolau volcanic activity by a long period of quiescence during which great erosion of the Koolau mass took place. The period of erosion was followed by one of deposition and valley filling, and the lavas and tuffs of the Honolulu volcanic series lie in and on the terrestrial and marine sedimentary beds formed at that time.

During the early period of great aggradation and subsequently, the volcanic products of the Honolulu series, and particularly the offshore tuff cones, have played a very important role in promoting growth of the sedimentary cap which serves both as a coastal plain and as an upper restraining member to the artesian systems of the Honolulu and Pearl Harbor areas. The offshore tuff cones apparently served first as stable headlands in the growth of corals and coral reef at various levels, especially at points somewhat remote from the mouths of the chief streams. The coral reef thus grown served as a platform, at various other levels, on which the stream-borne gravels and silts were deposited along the coast and offshore. The sections of many artesian wells show the intimate interrelation between coral reef and terrigenous sediments in the thousand feet of caprock at Honolulu (fig. 15) (Palmer, 1927). The marked development of the coastal plain caprock in the Honolulu and Pearl Harbor areas and the narrowing of the mouth of Pearl Harbor, can in large measure be attributed to the craters and accompanying lava flows of the Honolulu series. Similarly, by chance or otherwise, the valleys of the Honolulu area which have the deepest bedrock cut below sea level, and hence the most pronounced tongues of caprock fill (Palolo, Manoa, Nuuanu, and Kalihi), also include in that caprock fill considerable amounts of lava and tuff of the Honolulu volcanic series. These tuff and lava layers are generally weathered so that they are of low permeability and function as a part of the caprock. However, locally in some of the valleys certain members of the Honolulu series carry perched water or water with local artesian pressure quite distinct from the main body of artesian water.

Sedimentary rocks of both subaerial and marine origin are described under three main headings. The older group includes those members which appear to be older than the larger part of the Honolulu volcanic series. The intermediate formations are contemporaneous with the Honolulu series and those designated as recent include members younger than the late volcanics as well as the modern sediments of beaches and stream channels.

THE KOOLAU FORMATION

The Koolau formation consists almost wholly of basaltic lava flows erupted from numerous vents along a fissure line over 30 miles long. The flows average 10 feet or less in thickness, and the entire mass, from the deepest exposures some 2,000 feet below the dome surface to its top, shows exceptional uniformity. No evidence of general break in the deposition of these flows has been found, and the intrusive components consist only of dikes and sills which were emplaced incident to the growth of the mass. A few tuff beds are in places interbedded with the lava flows but do not, even locally, amount to over 5 per cent of the whole section. Throughout the whole mass the tuff lenses are certainly no more than 1 or 2 thousandths of the whole. The general physical uniformity is further verified by the uniformity in chemical composition and petrography (Wentworth and Winchell, 1947, p. 71).

BASALTIC LAVA FLOWS

Both pahoehoe and aa lava flows are common in the Koolau dome, with a preponderance of the aa flows in the better-exposed lower flanks of the mass. Because all flows are erupted first in the pahoehoe form, the inland parts of the mass, near the fissure zone or dike complex, probably would exhibit a greater proportion of pahoehoe flows; but no unweathered section has been found in which to verify this assumption. Even in the tunnel sections through the dike complex, abundant aa flows are found, and in various drill holes in the leeward section the aa flows constitute more than three-fourths of the whole.

It is important to emphasize that the aa flows include both the clinker phase with which most people are familiar and also the dense interior which is a component part of all aa flows. The latter is the only part useful for crushed rock and most other commercial quarry rock (Macdonald, 1945).

The lava formations are marked by various features typical of basaltic flows (Wentworth and Macdonald, in press). There is close-spaced jointing such that even in the thicker aa masses or in the pahoehoe it is impossible in quarry operations to produce any considerable fraction of 1- or 2-ton rocks. Regular polygonal or columnar jointing is, however, very rarely seen, and then only in an occasional thick flow.

The shapes of the upper and lower surfaces of flows are typical of pahoehoe and aa lavas and have been described elsewhere (Wentworth and Winchell, 1947; Wentworth and Macdonald, in press). The contact of lava flows, one on another, is marked by great irregularity occasioned by the broken character of the pre-existing surface and by the chilling and increase in viscosity of the advancing lava. Only between the successive thin units of pahoehoe flows is there any approximation to intimate molding of one flow on another so as to make what could be called a sealed joint. Elsewhere, and generally throughout the mass, the contacts show numerous openings, loose blocks, and abundant bridging, which contribute to the high permeability of the lava formation (plates V and VI).

Lava tubes are commonly encountered in any extensive tunnel through the Koolau mass and are exposed in outcropping cliffs. Most commonly these are 1 or 2 feet in diameter, but a number are known that are 20 feet or more wide and generally somewhat less in height. Often the floor is strewn with blocks dislodged from the roof, with considerable reduction of clear height. Some of these tubes can be followed for several hundred feet, and unquestionably they must contribute to the permeability and storage capacity of the formation.

Nearly all the Koolau flows are somewhat vesicular, according to their pahoehoe or aa classification. The pahoehoe flows have a rather regular distribution of vesicles, which often shows marked flow lines and intricate layering and interfolding. Some are cellular to a degree that makes them nearly pumiceous, but others have a much smaller percentage of vesicles, with dense material between. The aa dense masses in some places have almost no vesicles, but more commonly have a few large, irregular, or compound gas bubbles that are irregularly distributed in any surface of a few feet across.

The most important characteristic of the lava flow formation is its high permeability. This is due to the contraction joints normal to flow surfaces, the open spaces along most of the contacts, the lava tubes and lava bubbles, as well as to the open texture of many of the aa clinker layers. More detailed discussion of these hydrologic characteristics is offered in another section.

ASH AND TUFF BEDS

At various points in the Honolulu watershed area from Waialaenui to Kalihi there are beds of red, palagonitic tuff interbedded with the lavas of the Koolau formation. These are commonly 2 or 3 feet, more rarely 6 or 8 feet thick, and in most cases cannot be traced for more than a few hundred feet. They are not concentrated in any narrow zone but are best known in the section from central Manoa to Kalihi and within the first 1,000 feet below the surface of the dome (Wentworth and Winchell, 1947, p. 76). The most abundant exposures are in the head branches of Manoa Stream, particularly on the west side, and in the Nuuanu valley walls (plate VII).

The basal parts of these tuff beds commonly contain coarser fragments of accessory material broken from throat rock, but the upper parts consist of extremely fine-grained vitric material that is generally palagonitized (plate XI). This fine grain and the failure to find any recognizable vent structure have suggested that the individual explosions producing these beds must have been violent and that the material was blown some thousands of feet in the air. It has generally been believed that explosions of this character were of phreatic origin and derived their energy from steam produced by surface or shallow ground water. At one time the present writer felt that the explosions were probably caused by lava flows entering streams or surface pools or marshes. However, failure to find any number of such tuff beds in various other similar parts of the leeward slope suggests that the central Honolulu sector may be adjacent to a vent section where, during a certain period, there were recurrent eruptions that were both phreatic and productive of juvenile pyroclastics. The petrography of these beds is discussed below.

DIKES AND SILLS

Two categories of dikes and sills are included here. The larger number of these intrusives are included in the Koolau dike complex. This is a term offered first by Stearns (Stearns and Vaksvik, 1935, p. 95) and now in general use. It was applied by him to parts of the Koolau formation in which there are numerous dikes and which represent the main feeding system through which the growth of the dome was accomplished. Stearns states that the frequency of dikes is strikingly decreased in a short distance outside the margin of the dike complex. The present writer, in seeking a numerical definition of dike complex, believes that a formation containing 10 dikes to the mile would not be recognized by most field geologists as dike complex, but that one containing 100 dikes to the mile would be so regarded. This still leaves a somewhat desirable leeway in field mapping.

The dikes not in the main dike complex of the Koolau Range are scattered throughout the leeward part of the mass in the Honolulu area (Wentworth and Jones, 1940). They are more abundant at points near the dike complex and progressively less so toward the leeward margin. Their most marked occurrence is in a belt extending along the minor rift zone from Kaau Crater to Diamond Head.

PLATE V. Outcrop of pahoehoe lava flows, showing laminae and recurved arrangement of small vesicles and other textural features of pahoehoe. Koolau formation near Makapuu Head.

PLATE VI. Outcrop of aa lava flow in Koolau formation at Waialae quarry. The massive, dense interior with a few large, irregular vesicles is characteristic and in contrast to the finely vesicular texture of pahoehoe lava.

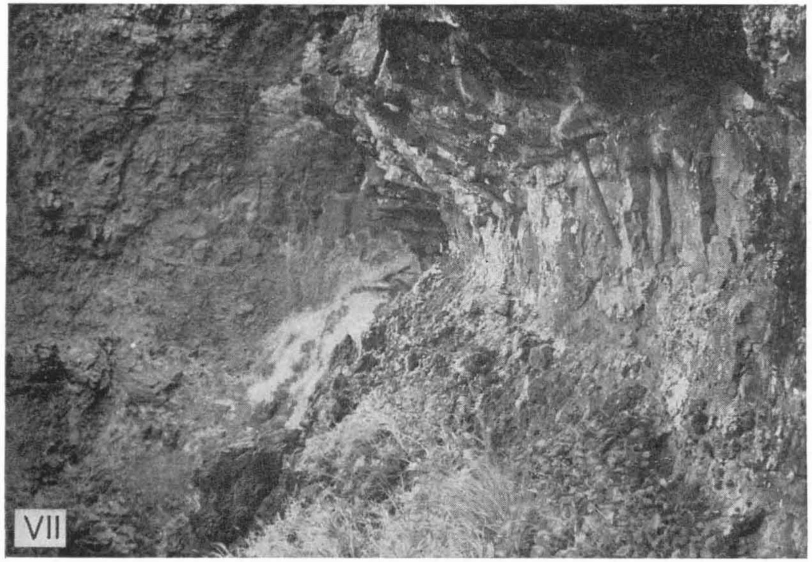

PLATE VII. Outcrop of Koolau tuff bed in small valley at inland end of Dowsett Highlands taluvial fan. The tuff is about 4 feet thick and its outcrop is eroded 2 or 3 feet back of the general surface of the rock wall. The lower part of the tuff bed is somewhat coarse and agglomeratic, but the upper part is fine-grained, originally vitric material altered to palagonite.

PLATE VIII. Dike in channel of Wailupe Stream, about 2 miles inland from the coast. This dike shows the usual columnar jointing as well as the splinter jointing near the ends of the columns. Note the contrast between the dense rock of the dike and the vesicular texture of the adjacent lava flows.

This rift zone appears to have had a part in volcanic action both in the building of the Koolau mass as shown by the dikes and also during the eruption of the Honolulu series as shown by Kaau, Mauumae, Kaimuki, and Diamond Head vents. Whether this rift zone is to be regarded as the "missing" south rift zone of the Koolau center as set forth by Winchell (1941, pp. 124–128) depends on whether a trifold arrangement of rift zones is regarded as a fundamental and necessary feature of each dome of the Hawaiian area. The writer has indicated elsewhere that it seems equally likely that some domes develop along a linear vent line and do not show any conspicuous fixing of a center or branching of rift zone in the manner postulated by Winchell (Wentworth, 1942, pp. 42–44).

The characteristics of the dikes and sills and other intrusive bodies have been described elsewhere (Wentworth and Jones, 1940, pp. 975–1006). It appears that the dikes are dense and columnar-jointed where they have been intruded at depths of several hundred feet but that the jointing is less marked and the dikes are banded and vesicular at lesser depths below the main dome surface. The spacing of the joints and sizes of the polygonal sections depend roughly on the thickness of the dike or component layer of dike and, as in sun-cracked mud and other such phenomena, the tensile strength of the layer in relation to contraction is the controlling factor.

Somewhat similarly, the thickness of individual dikes in the area outside the dike complex has been interpreted as limited by the amount of contraction in the lava flows in a width through which the rocks would tend to remain together as a unit (Wentworth and Jones, 1940, p. 985). The dikes recorded are mostly not over 2 or 2½ feet thick, but some reach 5 or 6 feet (plate VIII).

Sills are somewhat less abundant than dikes, and if we fully recognize the existence of cross joints through the mass, so that the lava flows are not continuous masses, it will be seen that in reality it is easier for a dike to be intruded through a crack that opens nearly vertically than for a sill to be intruded between flows or in flows where the superincumbent load has to be overcome. Neither the dikes nor the sills give evidence of a force of intrusion that exceeds the hydrostatic pressure needed to rise to the surface and hence approximately equal to the rock pressure at that point. The phenomenon is essentially that of a liquid rising through a mass of piled and frictionally interlocked blocks.

On the other hand, the denseness of the dikes and the tightness of the columnar joints, at most points a few score of feet deep, testify to the constraint of pressure as the dike cooled, and these characteristics are of enormous practical importance in hydrology. This condition is just the opposite of that mentioned for lava flows where the contact of one on another is not tight and nothing resembling a seal exists. The dikes are tightly sealed against the wall rock, and, though by contraction the pattern of the columnar jointing is established, the joints are not at depth opened sufficiently to pass much water, even under large pressure differences.

PETROGRAPHY OF THE KOOLAU ROCKS

A more detailed statement on the petrography of Koolau rocks, with petrographic descriptions of individual specimens and chemical analyses, has been presented elsewhere (Wentworth and Winchell, 1947, pp. 65–75). The petrography of the Hawaiian Islands has been summarized by Macdonald (1950).

Early studies had indicated very little variety in the mineral and chemical composition and had given no evidence as to changes in composition of the later flows of the Koolau series. In the detailed study here reported several hundred specimens of Koolau lava flows were sectioned and studied under the microscope, as well as many sections of dikes and a proportionately smaller number of sections of Koolau tuff. Finally, after much of the field work had been done, but while it was still actively in progress, specimens for chemical analysis were collected at various points in the Koolau mass in a special effort to locate possible variations in chemical composition. These analyses were made by F. A. Gonyer at Harvard University under a grant from the Geological Society of America.[2] Analyses of Koolau lavas, made both under this grant and otherwise, are included in table 1.

The analyses shown in table 2 indicate a comparatively slight range in composition, from 52.30 per cent to 48.28 per cent silica, with an average of 50.45 per cent. This composition corresponds very closely to large numbers of basalts in various parts of the world for which analyses are available (Wentworth and Winchell, 1947, table 5). However, the Koolau basalts are slightly more silicic than the average of 43 Hawaiian basalts and more like the 29 analyses from the island of Hawaii, both given by Cross (1915, p. 87) (fig. 5).

[2] Grant 297-39, to Committee on Hawaiian Petrology, for analyses of Hawaiian rocks.

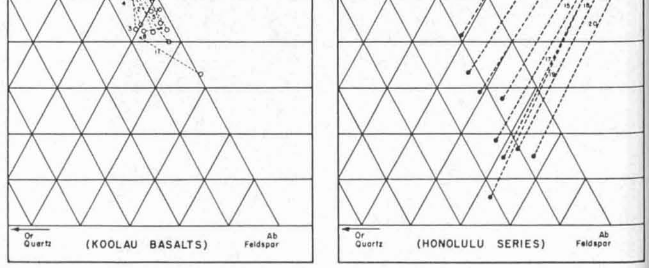

FIGURE 5. Variation diagrams for the Koolau basalts and for rocks of the Honolulu series. In each diagram the dots represent percentages of orthoclase, albite, and anorthite in the normative feldspar, the total calculated to 100. The circles are percentages of quartz (or silica) deficiency, feldspar and femic mineral, total also to 100 (Larsen, 1938). Numbers are the same as for analyses in accompanying table.

TABLE 1

LOCATIONS OF ANALYZED SPECIMENS, KOOLAU SERIES, OAHU

COLUMN NUMBER*	FIELD NUMBER	LOCALITY	POSITION	ANALYST
1	10398	Palolo Quarry	Thick dike in minor vent axis, probably late volcanic	Gonyer
2	10403	Makapuu Point summit	Near vent axis at east end, ca. 200–300 ft. below dome surface	Gonyer
3	10404	Kailua Road	Kailua volcanic series, relations not known	Gonyer
4	9980	West of Waimea Bay	Near dome shore, north end, ca. 200 ft. below dome surface	Gonyer
5	. . .	Nuuanu Pali	Saddle, ca. 3,000 ft. below final range crest, near vent axis	Washington
6	9986	Haiku Valley	Near vent axis, ca. 2,500–3,000 ft. below dome surface	Gonyer
7	9991	Waiakeakua Valley	Leeward valley, ca. 1,500 ft. below dome surface	Gonyer
8	(Cross No. 19)	Waimea†	North end of dome	Lyons
9	9948	Makapuu Highway saddle	Near vent axis at east end and less than 1,000 ft. below original dome surface	Gonyer
10	10396	Waiahole Valley	Windward valley, near vent axis, ca. 3,000 ft. below dome surface	Gonyer
11	11320	Moanalua Valley	Leeward valley, inland, ca. 1,500 ft. below dome surface	Gonyer

* See numbered columns in table 2.
† In the more widely used reference by Cross (1915), the locality is given only as Koolau Mountains, Oahu, leaving an unnecessary vagueness as to location.

TABLE 2

ANALYSES OF KOOLAU BASALTS

CONSTITUENTS	SPECIMEN NUMBERS											
	1	2	3	4	5	6	7	8	9	10	11	12
	10398	10403	10404	9980	*	9986	9991	†	9948	10396	11320	Mean**
SiO_2	52.30	51.94	51.20	50.97	50.80	50.59	50.08	49.88	49.62	48.74	48.28	50.45
TiO_2	1.68	2.58	2.49	2.14	2.55	2.18	2.08	3.97	1.51	2.42	3.70	2.33
Al_2O_3	14.80	14.18	14.62	13.72	14.42	15.34	15.80	13.79	12.68	15.98	17.86	14.94
Fe_2O_3	3.12	2.81	3.43	2.39	2.83	2.23	3.58	9.65	3.21	4.14	5.07	3.28
FeO	7.30	8.14	6.60	7.61	8.53	8.18	7.81	2.61	7.60	7.16	6.53	7.55
MnO	.05	.08	.10	.11	.09	.09	.11	.67	.09	.06	.06	.08
MgO	6.72	7.21	6.48	10.18	6.88	7.64	6.70	6.12	13.86	6.96	4.11	7.67
CaO	7.98	9.24	9.74	8.51	10.58	9.60	9.92	9.59	7.48	9.90	8.76	9.17
Na_2O	3.78	2.52	2.53	2.56	2.70	2.68	2.36	3.30	2.36	2.77	4.14	2.84
K_2O	.60	.35	.21	.61	.30	.11	.17	.17	.15	.22	.82	.35
H_2O-	.23	.12	.18	.08	.06	.27	.28	‡	.34	.70	.06	.23
H_2O+	.64	.59	2.20	.61	.31	.64	.74	‡	.67	1.19	.31	.79
CO_2	....	....	....	....	n.d.	....	....	‡	....	....	....	....
P_2O_5	.66	.35	.35	.28	.32	.15	.12	.26	.04	.08	.36	.27
SO_3	....	....	.03	.15	n.d.	.17	.15	n.d.	.05	.09	.02	.07
BaO	....	....	....	....	n.d.	....	....	n.d.	....	....	....	....
SrO	....	....	....	....	n.d.	....	....	n.d.	....	....	....	....
Cr_2O_3	....	.04	....	.07	n.d.	.05	.06	n.d.	.19	.04	.04	.05
Sum	99.86	100.15	100.16	99.99	100.37	99.92	99.96	100.01	99.85	100.45	100.12	

* Washington, H. S., Petrology of the Hawaiian Islands. Amer. Jour. Science, ser. 5, vol. 5, p. 487, 1923.
† Lyons, A. B., Chemical composition of Hawaiian soils, and of the rocks from which they have been derived. Amer. Jour. Science, ser. 4, vol. 2, pp. 421–429, 1896. Also in Cross (1915), No. 19.
‡ Analysis of ignited material.
** Omitting column 8.

Whether the differences of composition are taken as random variations or as indicative of some systematic differentiation or assimilation, they are nevertheless so slight that for all practical purposes they can be ignored. This uniformity of chemical composition is in accord with the results obtained from examination of hundreds of thin sections, where all the Koolau lavas are found to be normal basalts, olivine basalts, or hypersthene basalts which may or may not have olivine. It appears that variations between flows a few feet apart may be as great as those between flows widely separated horizontally or vertically. No systematic variation was recognized, and the chief random variations in composition seem to be between feldspar porphyries and olivine porphyries.

The textures of Koolau basalts are intergranular-porphyritic, with a range depending on the relative abundance of plagioclase laths. Glassy base is present in some. Phenocrysts are usually olivine, orthorhombic pyroxene, or plagioclase, any or all in any proportion up to a total of 50 per cent (plates IX, X).

Local contrasts chiefly evident to the naked eye are those between plagioclase porphyries and olivine porphyries. The most remarkable of the plagioclase porphyries is that noted first in upper Moanalua Valley and which contains plagioclase tablets ½ to 1½ inches across in amount up to 40 per cent of the rock. Flows of this type have been found in Halawa Valley, Haiku Valley, near the Luluku section of the windward pali, and also in the leeward slope of the range north of Schofield in the headwaters of Kawailoa Stream southwest of Puu Kapu.

Augite does not appear as phenocrysts. Magnetite and ilmenite are often included in the olivine phenocrysts, but rarely or never in the feldspar crystals, which crystallized later. Marginal alteration of olivine to iddingsite is common. Plagioclase is usually labradorite, often slightly zoned. Ground-mass minerals of the Koolau lavas are feldspar, olivine, rhombic pyroxene, augite, magnetite and ilmenite, very sparsely distributed apatite, and occasionally some glass.

OLDER SEDIMENTARY FORMATIONS

The oldest sedimentary formations preserved in the Honolulu area are the gravel and other alluvial beds that lie on the Koolau surface at the base of the caprock. Some of these, in offshore positions only slightly known in drill holes, may correspond to the very last stages of the erosion of the deeper valleys. Next younger are the alluvial formations that lie on the rock surface at the bottom of these deeply eroded valleys and which were deposited after the end of the most intense erosion. These formations range upward through the period of aggradation without recognizable widespread break until the time of the earliest eruptions of the Honolulu series.

No designation for these formations more suitable than alluvium has been devised. Some parts are of fine grain and show no boulders; other beds carry blocks and boulders up to several feet in diameter. Much of the material consists of ill-sorted slope wash accumulated on steep valley sides. Very little of it is well-sorted stream sediment. This is partly due to the shortness of the stream channels and partly to the fact that in the weathering of basalt no hard minerals are released and under stream conditions very little hard gravel is produced at any one time (plate XII).

An outstanding characteristic of the older alluvium is that it is so generally weathered to a soft, ferruginous mass. Usually the larger blocks show conspicuous spheroidal weathering, and only rarely do small central kernels consist of sound basalt. The whole mass is generally mottled with delicate color difference in reds, browns, dark purples, and yellows between the matrix and the different cobbles and blocks. Color arrangement is usually sufficient to permit discrimination of the detrital alluvium from equally weathered lava flows, but, even where that fails, the structures, as indicated by vesicle arrangement, usually permit discrimination of the detrital alluvium from lava flows.

The great importance of the old alluvium in groundwater and hydrologic studies lies in its very low permeability. This has come about through the volume increase that attends the weathering of basalt. It depends also on such weathering taking place under a considerable load of overlying material. The old alluvium is tightly rammed and compact, with no original spaces larger than vesicles remaining open. Pressures developed by the volume increase have closed up all the larger openings, the diameter of a dome that is competent to remain open in a given material being inversely as the unit pressure. The weathered material does not have high crushing strength, hence it has the capacity to seal off openings in other materials by being rammed under its own continuing pressure, and the openings which may develop in it are similarly sealed.

Other formations associated with the old alluvium in the caprock and caprock tongues in some degree resemble it. However, it is unquestionably the most important element in the functioning of the caprock as a water barrier. The larger part of the formation is still buried and it is commonly found directly on the surface of the Koolau rock throughout the valley-bottom and coastal-plain area.

OLD MARINE FORMATIONS

Only very little is known of the older marine formations. The logs of many drill holes show coral more abundant in the first 200 feet below sea level, but lesser amounts of coral are reported from greater depths. No evidence is known of coral or other marine formations that clearly antedate the beginning of the period of aggradation and, though coral appears sporadically in the lower parts of the caprock, we may conclude that its growth in general was not very active until after general offshore deposition of terrigenous materials had somewhat abated. Some of the latter may have been sufficiently reworked by the sea so as properly to be called marine,

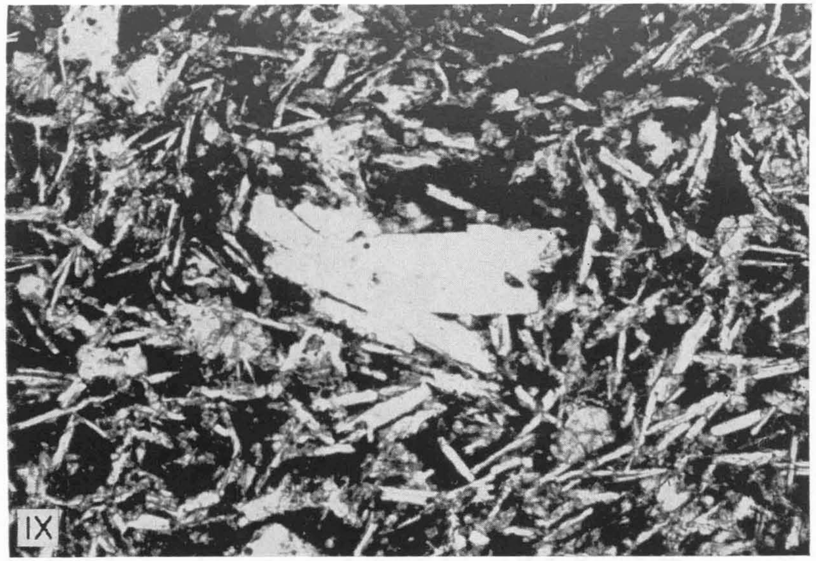

PLATE IX. Photomicrograph of Koolau basalt, from diamond drill hole number 8, south of spillway to Reservoir No. 2, Nuuanu Valley, at depth of 249 feet, elevation 466 feet. Large crystal of feldspar in center has a length of 4/10 millimeter.

PLATE X. Photomicrograph of Koolau dike rock, from outcrop near junction of Kaau outlet stream and Waiomao Stream. The larger feldspar crystals are about ¼ millimeter long.

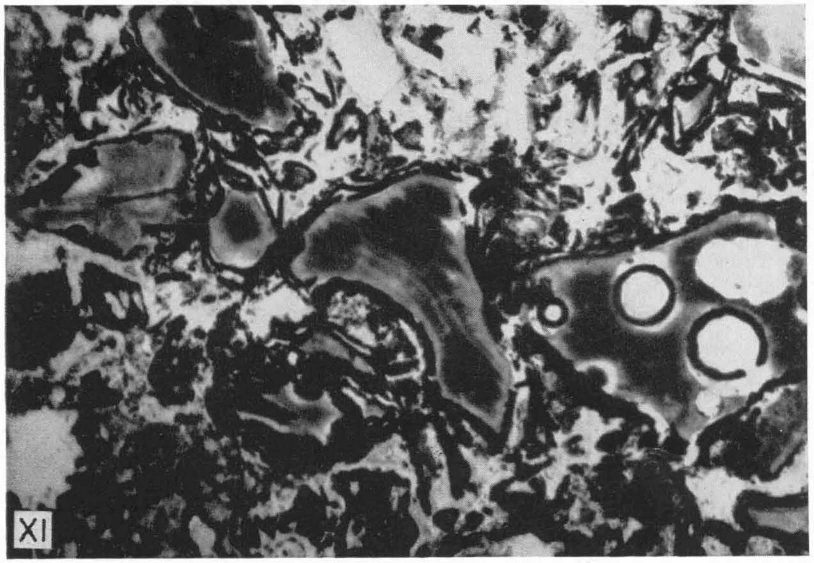

PLATE XI. Photomicrograph of Koolau tuff, locality number 10377, west wall of Kalihi Valley near its head, at 1,400 feet. The specimen contains fragments of crystalline basalt but consists largely of a fine-grained assemblage of palagonitized glass fragments, mostly in vesicular, shard shapes, which show a banded structure, of flow origin. The large shard at the center is ¼ millimeter long.

PLATE XII. Weathered old alluvium in road cut, Maunawili. This surface is etched by weather to a relief of 1 or 2 inches after being cut by road-working tools across matrix and boulders alike. Practically all parts can be cut easily with a mattock or hoe.

but relatively little material of character distinct from the old alluvium and of clear antiquity is known. Many of the drill logs report "clay." This can be either weathered alluvium, or weathered marine beds derived from the same source, or a weathered zone of the undisturbed Koolau formation. Deep burial and weathering brings to all three of these materials very similar characteristics, as shown in drilling. Lacking access to such material to see its general structure or other features that might permit definite identification as marine, we cannot attach great significance to it in interpretation.

HONOLULU VOLCANIC SERIES

THE SOURCE VENTS

The members of the Honolulu volcanic series were erupted and deposited on a much-eroded, mature topography which had already been carved from the Koolau dome following its building. Hence, these tuff cones and lava flows are materially younger than any of the Koolau rocks and are separated from them by a major break in the geologic history of Oahu. The distribution of the vents from which these later rocks came is shown on an accompanying map (fig. 6). The vents are restricted to the southeastern end of the Koolau Range and appear on both its windward and leeward sides.

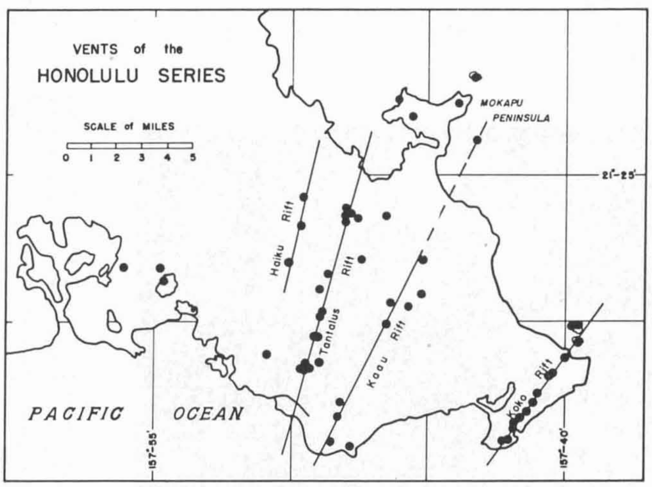

FIGURE 6. Sketch map showing vents of the Honolulu series. The rift lines as shown are based on field evidence supplemented by petrographic similarities. (After Winchell, 1947.)

The various members were erupted through a considerable period within the Pleistocene and their ages have been discussed by Stearns and Vaksvik (1935) and later by Winchell. Table 3, compiled by Winchell (1947, p. 5), summarizes present understanding.

A number of these vents are arranged in lines, and at least one line, the Kaau–Diamond Head line, coincides with the trend of the Koolau dike zone extending from Palolo quarry inland to the crest of the Koolau Range. Stearns has discussed the arrangement of these vents and pointed out that they lie in lines trending northeast-southwest, approximately normal to the crest of the range and to the main rift line of the Koolau volcano (Stearns and Vaksvik, 1935, pp. 163–164). He has also stated that these lines radiate from masses of throat breccia of the Koolau series, which he takes to mark the center of eruption in the Koolau volcano. This would be an entirely plausible relationship, but it seems to the present writer that the radial pattern is scarcely demonstrated and that the presence of these vents at the southeastern portion of the Koolau mass, together with the supposed throat breccia, are together suggestive only of a moderate concentration of volcanic activity in this part of the range.

The writer believes that the primary form of volcanic outpouring is that of a linear vent and that such vent may, or may not, become fixed and transformed to a central type. The evidence is so strong for the general preponderance of linear activity in the Koolau dome that it seems an open question whether there was ever a central vent or a caldera. Such an interpretation must rest on field data, mostly not discovered, rather than on a too-ready supposition that a volcano must have a caldera at some stage.

From these secondary vents came magma which took three forms. Some of the products form cinder or agglomerate cones, such as Tantalus and Sugarloaf, surrounding the vents. A number of other cones are wider rings, like Diamond Head or Punchbowl, and these are composed of tuff. Finally a number of vents have given rise to lava flows which extend down the valleys like those in Nuuanu or Kalihi or which form large lava cones like Kaimuki.

The members of the Honolulu series of the windward or Koolaupoko section of Oahu do not fall in the Honolulu–Pearl Harbor area. However, they are so closely related to the remainder of the series that they will be described here in geographic order but in slightly less detail than those of the leeward slope. The writer has made first-hand studies of most of the windward Honolulu volcanics and in the following section has drawn both on his own notes and on data published by others (Wentworth, 1926; Stearns and Vaksvik, 1935; Winchell, 1947).

PETROGRAPHY OF THE HONOLULU SERIES

The lavas of the Honolulu series differ greatly from the Koolau lavas and also show wide differences in composition among themselves. They range from about 5 per cent to about 15 per cent less silica than the Koolau rocks, and show on the other hand an excess of nearly every other constituent over the corresponding amount in the Koolau series (Winchell, 1947, p. 34) (fig. 5). The most abundant lava types of the Honolulu series are nepheline and nepheline-melilite basalts.

Nearest to the Koolau rocks is the linosaite (Anal. 12)[3] of the Koko lava flows. At the other extreme are the Kalihi and Puu Hawaiiloa nepheline-melilite basalts

[3]The designations in this paragraph correspond to specimen numbers shown in table 5.

TABLE 3

GEOCHRONOLOGY OF OAHU*

TERTIARY

Waianae dome growth and earliest Koolau dome growth
Extinction of Waianae volcano; overlapping by Koolau volcano

EARLY (?) PLEISTOCENE

Extinction of Koolau volcano; very long erosion interval
Lualualei (–1800-foot) stand (evidence on Oahu)

MIDDLE (?) AND LATE PLEISTOCENE

Mahana (1200-foot) stand (evidence on Lanai, traces on Oahu)
Manele (560-foot) stand (evidence on Lanai, traces on Oahu)
Olowalu (250-foot) stand (evidence on Maui, traces on Oahu)
Kahuku (55-foot) stand

	Honolulu Series Stearns–Vaksvik	(Winchell)
Kahipa (–300-foot) stand		Hawaiiloa Pali Kilo Pyramid Rock Moku Manu (?) Ulupau (?) Mokolea (?)
Kaena (95-foot) stand	Hawaiiloa Mokapu Mokolea Rocky Hill Kalihi Haiku Aliamanu Kaneohe Nuuanu Pali Makawao (Koolau?) Moku Manu	Kalihi Haiku Rocky Hill Aliamanu Kaneohe Luakaha Makuku } Nuuanu Pali Makawao = (Koolau?) Kaau
Laie (70-foot) stand	Ulupau Kaau	Mauumae
Waipio (–60-foot) stand	Salt Lake and Makalapa Ainoni Maunawili Training School Diamond Head Kaimuki Mauumae Black Point Kamanaiki Punchbowl	Salt Lake and Makalapa Ainoni Castle Maunawili Training School Diamond Head Kaimuki Black Point Kamanaiki Punchbowl
Waimanalo (25-foot) stand	Castle (Waipio?)	
LATEST PLEISTOCENE OR RECENT		
9 Kapapa (5-foot) stand Modern stand	Koko group Tantalus group	Koko group Tantalus group

* Reproduced from Winchell (1947).

(Anal. 18 and 20). The composition and petrographic classification of the several lava flows is given in each of the descriptions that follow, and the general problem of their origin has been discussed by Winchell (1947, pp. 27–48) and by Macdonald (1950, pp. 1580–1588). Analyses are set forth in tables 4 and 5 and the relationship in composition to the Koolau series is shown in figure 5.

HAIKU BASALT AND TUFF

The known Haiku vents are located several hundred feet above the valley floor on the two sides of the blunt, rounded head of Haiku Valley. They correspond both in position and trend with the Koolau dike complex, and the Haiku magma apparently followed this old fissure system to the surface. Because of the high ground water confined in the dike complex, the early part of the eruption was marked by steam explosions and produced fine ash which altered to the type of brown tuff more commonly found in the shore craters like Diamond Head (Stearns and Vaksvik, 1935, p. 107).

The tuff is a blocky, red-buff, somewhat gritty rock marked by a few large red grains of palagonite and by dark grains of both Koolau and Haiku basalt. The tuff ranges up to 30 feet thick and underlies at least part of the weathered alluvium. It is exposed in the banks and channels of the head branches of Haiku Stream and with lesser thickness is a component of the terrace section farther seaward.

The Haiku basalt has the usual massive form and jointing of Honolulu basalts and is exposed at various places in the Haiku channel, in the base of bluffs at the margin of stream flats, and along the coast east and west of the Pohakea Koolau remnant. This basalt is the aquifer which supplies Baskerville Springs, and it has been penetrated in test drill holes inland from the springs. According to Winchell (1947, pp. 54–57) the Haiku lava is a nepheline basalt containing little if any melilite except in certain segregations.

KANEOHE VOLCANIC ROCKS

The Kaneohe volcanic rocks consist of a cluster of cinder cones 2 miles south of Kaneohe and which mark the vent and a lava flow exposed over perhaps a square mile to the northward. No palagonitic tuff is known, and explosions were apparently wholly magmatic. The Kaneohe lava is nepheline basalt which is some places contains melilite and is thus similar to the Haiku basalt (Winchell, 1947, pp. 9–10). It is of limited importance as a water bearer. A similar, smaller group of cinder cones and a small lava flow of the same series lie about 2 miles east at the head of Kawainui Swamp.

AINONI–TRAINING SCHOOL BASALTS

Lava flows of the Honolulu series are found in each of the two head branches of Maunawili Stream. One at the east came from a vent practically on the Aniani Ridge divide between Maunawili and Waimanalo and the other from a vent at the base of the pali north of Mt. Olympus. This is the flow carrying water which issues at Ainoni and Ape Springs near Maunawili Ranch. A third and larger lava flow issued from a vent in the slope of Olomana, inland from the Training School. This flow extends nearly 2 miles seaward between Kawainui Swamp and the Puu o Ehu Koolau remnant. Along the bluff facing the swamp its large blocks among the papaya trees have long been conspicuous to travelers on the highway toward Kailua Junction. In 1938 the writer found a few blocks of Training School basalt at 500 feet in the next ravine, 1,000 feet farther west than the main vent, suggesting that the basalt trickled down this depression also.

PALI VOLCANICS

In addition to small lava flows, both magmatic and phreatomagmatic pyroclastics are found near the Nuuanu gap and in remnants down the pali slope. The latter materials indicate the occurrence of steam explosions which were apparently due to ground water confined in the dike complex (Stearns and Vaksvik, 1935, p. 116). The lower part of the pyroclastic material is coarse, contains fragments of Koolau rock, and grades upward to finer-grained, magmatic cinders and ash. Both the pyroclastic beds and the lava are strikingly unconformable in relation to the steep pali slope on which they are laid, and it is probable that there was contemporaneous slumping, as well as rapid erosion, following the eruption. Both the breccia which occurs near the Nuuanu gap and the dike described by Stearns from the outcrop on the Pali Road indicate that the source of the Pali volcanics was near the gap, but the exact structural relations are not apparent.

Stearns considered (Stearns and Vaksvik, 1935, pp. 116–117) that the Pali volcanics are younger than the Nuuanu volcanics since a layer of "fine pumice" attributed to the Pali vent is found interbedded with alluvium in the area of Reservoir No. 4 where it overlies Nuuanu basalt. The diamond drilling in Nuuanu Valley revealed a succession of lava flows and other volcanic formations, evidently erupted at somewhat extended intervals from the Makuku and Luakaha vents, and the present writer believes that this cinder bed found at various points in the reservoir area is just as likely from a late eruption at the Makuku vent. Moreover, in the light of the probable topographic history of Nuuanu Valley and the close relationship between the cinder beds and the present surface, the attribution of this cinder bed to the Pali vent does not seem consistent with the dating of the Pali vent eruption with a stage as early as the Kaena.

Only a very small area of the Pali basalt has been found, at about 500 feet, above one of the turns of the old highway below the Halfway House. A few small trickle flows are interbedded with the cinders and breccia from the same vent, all on the windward slope of the range.

The Pali lava flow is a nepheline basanite. It contains considerable olivine, as well as plagioclase, nepheline, pyroxene, and magnetite, with minor amounts of biotite and apatite. The olivine shows central areas of lower

TABLE 4

LOCATIONS OF ANALYSED SPECIMENS OF HONOLULU SERIES ROCKS*

COLUMN NUMBER†	FIELD NUMBER	NAME AND LOCALITY
12	9962	Linosaite from lava flow in small gulch north of Hanauma Bay, elevation 130 feet
13	9982	Nepheline basanite from south tip of Black Point, near sea level
14	10402	Nepheline basanite from Kalama Crater flow, east side of Kamehameha Highway between Koko Crater and Makapuu Head, elevation 10 feet
15	9961	Nepheline basalt from lower Nuuanu (Luakaha) flow above Kapena Pool, elevation 170 feet.
16	10399	Nepheline-melilite basalt from Kaau lava flow, east side of Waiomao Road 250 feet from north end, elevation about 600 feet
17	10400	Nepheline basalt from Training School flow on east side of Kamehameha Highway, 0.3 mile southwest of Kailua Junction, elevation about 30 feet
18	9960	Nepheline-melilite basalt from Kalihi lava flow in Kalihi Stream channel at old forest reserve boundary, elevation 600 feet
19	Cross (1915) p. 22	Nepheline-melilite basalt from Moiliili Quarry, known as Sugarloaf flow
20	10401	Nepheline-melilite basalt from flow north of Puu Hawaiiloa, Mokapu Peninsula, elevation 50 feet
A		Average of columns 12 to 14
B		Average of columns 15 to 20

* Locations in greater detail are given by Winchell (1947).
† See numbered columns in table 5.

TABLE 5

ANALYSES OF HONOLULU BASALTS

CONSTITUENTS	SPECIMEN NUMBERS										
	12	13	14	15	16	17	18	19	20		
	9962	9982	10402	9961	10399	10400	9960	*	10401	A	B
SiO_2	45.13	42.86	43.94	38.57	36.72	37.10	36.75	36.34	37.22	43.98	37.12
TiO_2	2.94	2.94	2.32	2.79	2.82	2.90	2.41	2.87	2.02	2.73	2.64
Al_2O_3	16.40†	11.46	12.60	11.71	11.56	11.12	11.98	10.14	12.08	13.49	11.43
Fe_2O_3	3.42	3.34	3.84	5.21	4.94	6.53	6.05	6.53	5.18	3.53	5.74
FeO	8.17	9.03	9.18	7.78	8.17	7.31	7.45	10.66	7.88	8.79	8.19
MnO	.07	.13	.09	.11	.13	.09	.08	.20	.11	.10	.12
MgO	5.52†	13.61	11.43	13.08	13.27	12.81	12.08	10.68	12.71	10.19	12.44
CaO	11.30	11.24	10.78	12.84	14.34	13.56	13.81	13.10	13.34	11.11	13.50
Na_2O	3.62	3.02	3.84	4.22	3.93	4.56	4.75	4.54	5.12	3.49	4.52
K_2O	1.02	.93	1.02	1.20	.62	1.20	.91	1.78	.71	.99	1.07
H_2O-	.42	.12	.02	.19	.41	.04	.36	1.00	.23	.19	.37
H_2O+	1.16	.44	.36	.59	1.63	1.11	1.61	1.00	1.73	.65	1.28
CO_2	.05	none	none	.27	none	none	none	.15	none	.02	.07
P_2O_5	.66	.52	.43	1.11	.82	1.19	1.41	1.02	1.40	.54	1.16
SO_3	.17	.22	.21	.17	.31	.34	.17	.10	.17	.20	.21
BaO	.06	.04	.08	.08	.11	.13	.13	n.d.	.12	.06	.11
SrO	none	none	none	none	none	none	none	n.d.	none	none	none
Cr_2O_3	none	.04	none	.06	.07	.04	.03	n.d.	.03	.01	.05
Sum	100.11	99.94	100.14	99.98	99.85	100.03	99.98	100.11	100.05	100.07	100.02

* See Cross (1915), p. 22.
† Confirmed by a chemical check by F. A. Gonyer, Harvard University.

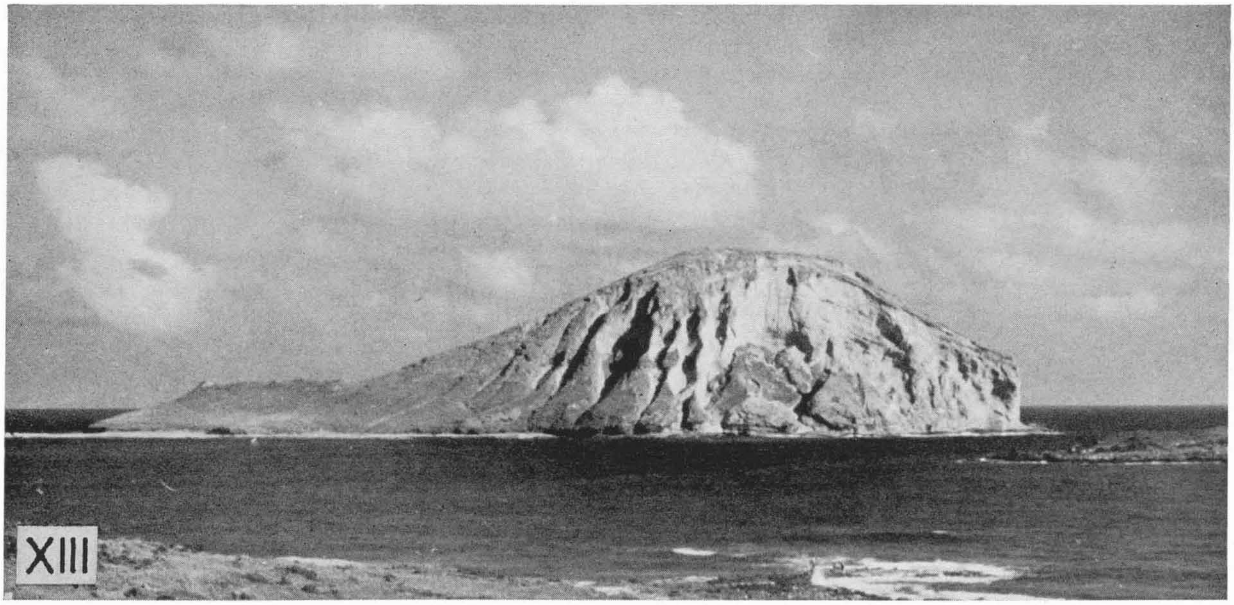

PLATE XIII. Manana Island, a double tuff cone of the Honolulu series, resulting from submarine explosive eruptions off the windward coast of the east end of the Koolau Range. Perhaps because of deeper water, this cone was never enclosed by the coral reef which ties to the smaller island nearer to Oahu (right).

PLATE XIV. Air view of the Koko peninsula from the southwest. From the near end in order, are Koko Head, Hanauma Bay, Koko Crater, and, at background, the spurs and saddles of the Koolau Range with Manana Island beyond. (Courtesy of Aero Photo Surveys.)

birefringence, surrounded by more highly birefringent zones, and there is often a rim of iddingsite. The plagioclase is labradorite (Winchell, 1947, pp. 11, 29).

HONOLULU VOLCANICS OF MOKAPU PENINSULA

This peninsula owes its origin to the late eruptions which formed the palagonite tuff crater of Ulupau Head and the vent cone and lava flow of Puu Hawaiiloa, Pali Kilo, and Pyramid Rock. These masses were the salients permitting growth of coral reef which resulted in their merging with the main island of Oahu. The group includes also the Moku Manu islands, the rock Mokolea, a mass of Honolulu basalt between Ulupau Head and Puu Hawaiiloa which Stearns has called the Mokapu basalt, and another that lies in the reef of Mokapu Landing (Winchell, 1947, pp. 6–8, 28–34).

These volcanic masses have been described by the author and others elsewhere, and no great elaboration is required here. The Hawaiiloa cone, 337 feet high, is composed of cinders and is the source of 100 feet of lava that flowed northward and formed also Pali Kilo and Pyramid Rock, the latter since isolated by erosion. Ulupau Head is the eroded remnant of a tuff cone which ranked in size and height with Diamond Head. It was formed later than the Hawaiiloa cone and flow. The Moku Manu islands are remnants of a tuff crater and crater-filling lava which indicate a distinct vent. Whether the advanced stage of erosion is due to a greater age than Ulupau Head as suggested by Stearns (Stearns and Vaksvik, 1935, p. 121) or merely to greater exposure to the sea, as seems equally likely, is not made certain by any evidence yet discovered.

The Mokapu basalt outcrop, the Mokolea islet, and the Ulupau (dike?) basalt are all of small area above sea level and chiefly of geologic interest only (Wentworth and Hoffmeister, 1939, p. 1560; Winchell, 1941, p. 46; Winchell, 1947, p. 7).

MANANA (RABBIT) ISLAND

Manana Island, a mile off the windward coast, 2,000 feet in diameter and 361 feet high, is the eroded remnant of a tuff cone. Its form indicates that two vents were active during the eruption, and the structure of the inner part of one of the components is strikingly shown in the great water-leveled bench on the windward side of the island (Wentworth, 1938, pp. 15–19). This island, perhaps because of its position near the Makapuu end of the range, was formed in deep water, is wholly outside the present reef, and apparently, unlike Ulupau, was never joined to Oahu (plate XIII). It is the northernmost of the vents along the Koko line (Wentworth, 1926, pp. 78, 84–85; Stearns and Vaksvik, 1935, pp. 149–150). No lava flow from the Manana Island vent is known. The rock contains melilite, which raises an interesting question on its relationship to the Koko series.

KAOHIKAIPU ISLAND–KAUPO FLOW

This island is only 80 feet high and is composed of red cinders with irregular dikes, indicating a vent; a pahoehoe lava flow appears on the seaward half of the island. Southwestward, at the foot of the windward cliff on Oahu, is a small fan of late Kaupo lava from a vent at about 250 feet elevation. These two vents are on the rift line of the Koko series, and the lavas are olivine basalts similar to the Koko series. Lack of Manana tuff on these lavas suggests that they may be later than Manana Island.

THE KOKO VOLCANIC ROCKS

Most conspicuous of the Koko group are Koko Crater, Hanauma Bay (Crater), and Koko Head Crater, all composed of palagonite tuff and forming a rugged peninsula 3 miles long and 1 mile wide (plate XIV). This mass extends obliquely southwestward from the southern margin of the Koolau Range. Koko Crater is markedly unsymmetrical, with its high leeward peak reaching 1,204 feet above sea level; its opposite rim either was never formed or has been breached. It is on a base 1.5 by 2 miles at sea level and is but moderately eroded by rills and by the sea on its south side.

The Hanauma Bay Crater is a mass about 3,000 feet in diameter at the rim and cut away or never formed on the sea side. There were at least two eruptions, and tuff from other vents undoubtedly makes up part of the mass (plate XV). The Koko Head mass is a complex pile reaching 644 feet above sea level with depressions suggesting several separate vents. The whole shows a rounded topography due, apparently, to successive mantling by ash from various eruptions, including those to windward as far as Koko Crater. The northeasternmost vent on the leeward side of the range is Kalama Crater. This is a small, rimmed depression not over 500 feet in diameter in the mouth of Kalama Valley on the south flank of the Koolau Range. Surrounding the depression is a somewhat elongate mass of cinders and spatter material, and from it a lava flow extends south and east to form about a mile of the present coast. The thickness of the lava flow is not known. The rim of Kalama is overlain by a thin layer of Koko tuff, showing that its eruption was earlier than at least some of the explosive phases of Koko Crater or other vents of the series. Next southwest of Kalama is a small dike vent on the northeast slope of Koko Crater, marked by spatter and a detached area of lava farther down the slope.

The main vent of Koko Crater, with the summit peak Puu Mai, is next in line and is indicated by the regular asymmetry of that mass; but any vent materials are covered by alluvium within the bowl of the crater (plate XVI). On the southwest slope of Koko Crater at about 300 feet elevation is a small dike vent, source of a small lava flow which reached the sea and of which small remnants remain. Fifteen hundred feet farther southwest is a flat-bottomed explosion crater showing no magmatic material at all. Between that crater and Hanauma Bay are two more vents on the same rift line. From one, a small lava flow passed down a depression and reached the sea east of Hanauma Bay. From the other, lava trickled over the wall of Hanauma Bay and onto the bench east of the head of the bay. On the

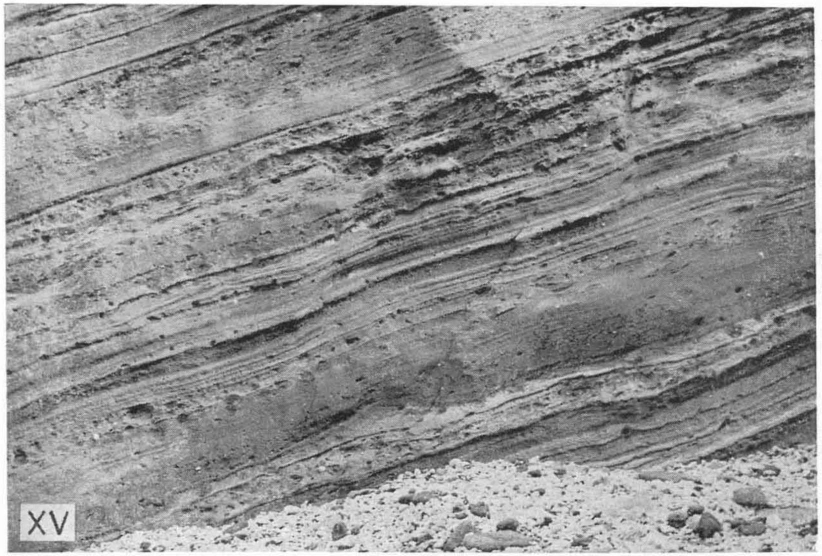

PLATE XV. Koko Head tuff outcrop on west shore of Hanauma Bay. At the base is coral and tuff gravel in a small pocket beach several feet above sea level. This outcrop shows the parallel mantle bedding and slight textural differences emphasized by wave and spray etching, as well as the lack of sharp division into specific beds.

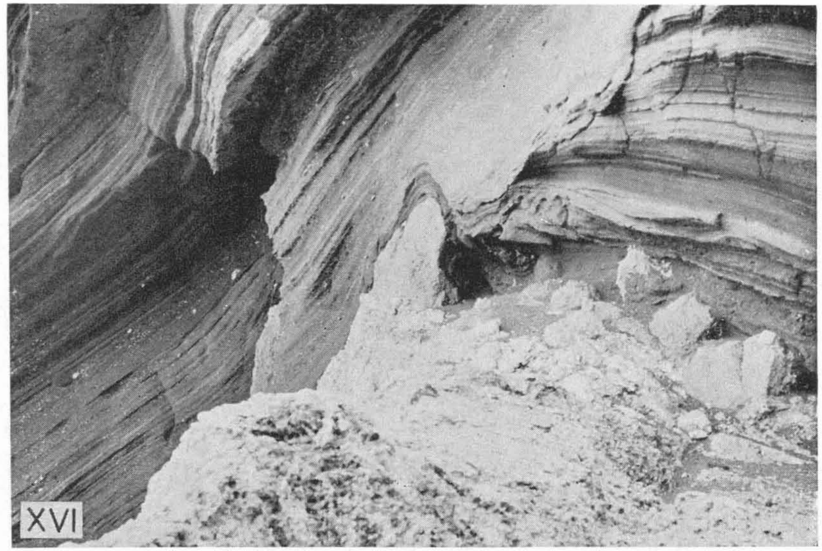

PLATE XVI. Mantle bedding in Koko Crater tuff, with unconformity between steep beds at left and nearly horizontal beds at right, the latter resting on eroded coral reef rock. The upper unconformity may represent but a few hours' or days' interval, the earlier tuff having slumped, probably into the sea, at the left.

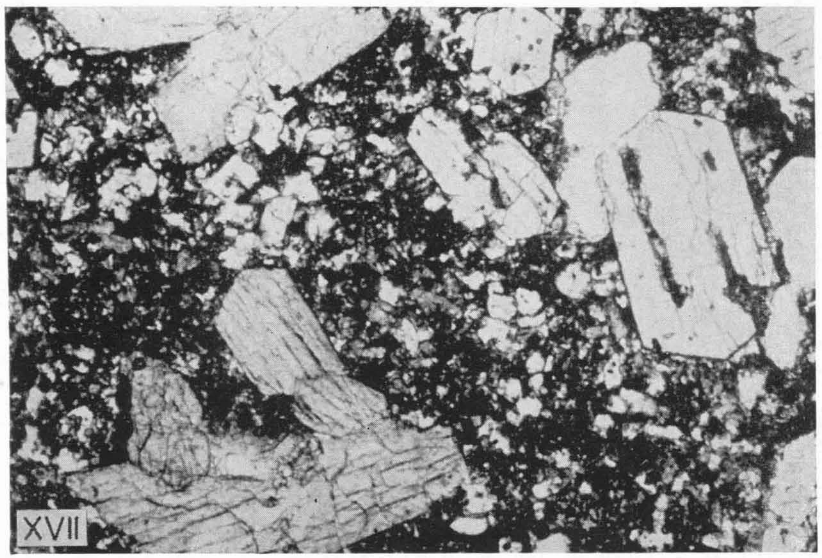

PLATE XVII. Photomicrograph of Mauumae basalt of the Honolulu series, showing large, clustered augite crystals (lower left) and olivine crystals of similar size (right). The latter is about 0.8 millimeter long.

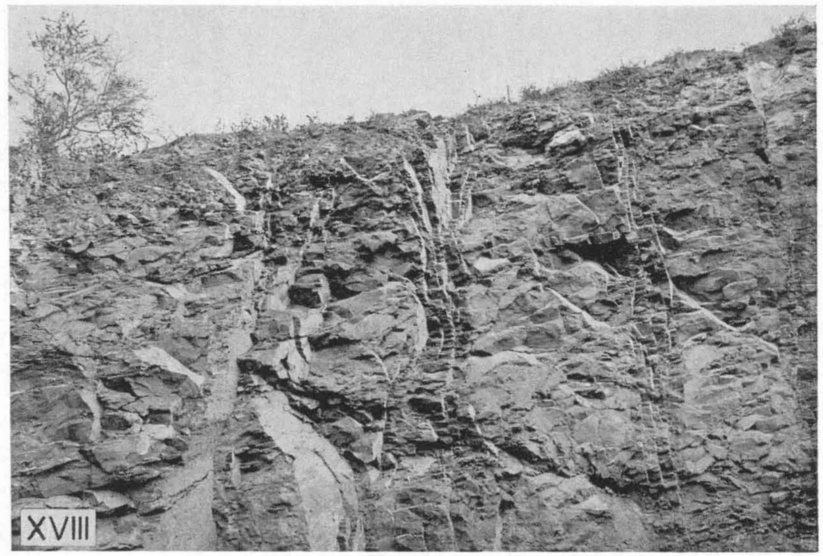

PLATE XVIII. Diamond Head tuff in the excavation for Diamond Head reservoir. The sedimentary layers, parallel to the surface and dipping from right to left, are comparatively faint and do not materially influence weathering in an outcrop. The vertical joints are radial to the circle of the crater as a whole and cut across the ring to accommodate tangential expansion and contraction.

western side of Hanauma Bay is a small lava flow interbedded in tuff, and the topography of Koko Head suggests at least two vents under that mass.

Only a few of the age relationships are known. The Hanauma Bay and Koko Head masses are both complex and include a late tuff which overlies, with marked unconformity, the earlier tuff. It should be recognized, however, that such unconformity could be produced by marine erosion or contemporary slumping and would mean only a short break in local conditions; no soil zones or other indications of a long time interval have been found. In the Manana Island area the Kaohikaipu and Kaupo lava flows appear to be later than the Manana Island tuff. On the leeward side, the latest Koko Crater tuff is younger than the Kalama Crater rim, at least by a few days, and no significant amount of the Koko Crater or other tuffs of the area can be younger than the several small flows that lie at the surface between Koko Crater and Hanauma Bay.

According to Stearns (Stearns and Vaksvik, 1935, p. 153), the lava of the Kalama flow carries a mineral identified tentatively as nepheline, a fact which would correlate it with the Manana Island tuff and distinguish it from the Kaupo and Kaohikaipu lavas. Thus it may be that Manana Island and the Kalama flow are representatives of an older magma. Whether lower parts of the other craters in the group can be correlated petrographically with these is not shown by any available evidence.

Winchell (1941, p. 110) considers that the whole series is derived from one magma, "a nepheline basanite carrying much feldspar and rather little felspathoid" (plate XVII). This view, however, does not wholly resolve the problem of variations in composition shown by different components of the Koko group, and further petrographic work here would be of interest to specialists. Until more data are available, we may as well accept the view of all students so far, to the effect that the Koko eruptions, while separated by some slight breaks and not strictly simultaneous, took place during a short space of perhaps a few weeks or months.

MAUUMAE VOLCANICS

The Mauumae cone lies on the western corner of the Kapahulu flow-slope facet, its western base and northeast saddle lying at elevations of 130 and 275 feet, respectively. The summit reaches about 350 feet above sea level. Its exposed portion is composed largely of cinders and driblet scoria beds (rhyoclastic material) with a few interbedded trickle flows (plate XVIII).

The cinder beds from this vent are well exposed in the quarry on the west side. The cone was first reported as olivine-feldspar basalt both by Cross (1915, p. 19) and later by the present writer (1926, p. 92). With more detailed collecting it is found that the basalt of the cinders and trickle flows is in reality nepheline-melilite basalt, a member of the Honolulu series (Powers, 1920, p 273). Thus Powers alone of early observers collected nepheline basalt from the valid lava product of this vent on the northwest side. The erroneous identifications were based on specimens from the eastern slope of the hill which is composed of Koolau basalt, possibly preserved from erosion by Mauumae products only recently stripped off.

In the core of diamond drill hole 20, in the Liliuokalani School grounds, Mauumae basalt occurs from elevation 125 feet to below present sea level. This basalt is overlain by only about 50 feet of Kaimuki lava, which is plagioclase basalt. Likewise, in the Kapahulu quarry the basalt flows which have hitherto been regarded as derived from Kaau Crater, appear on closer study to have come from the Mauumae vent. If this identification is correct, Mauumae was in eruption prior to Diamond Head or Kaimuki, though it is not necessarily demonstrated that the upper cinders and flows were produced so early.

The Mauumae tunnel, driven by the Board of Water Supply on the line of Keanu Avenue, revealed the relationship of the Mauumae volcanics to the Koolau rocks and the Koolau ridge. This tunnel is one block inland from Waialae Avenue, at the elevation of 120 feet, and has a total length of 1,413 feet from 11th Avenue to Wilhelmina Rise. This drift entered the wall of the old cinder quarry and passed through steeply dipping Mauumae cinders, followed by coarser driblet. Between 230 and 530 feet the tunnel penetrated massive Mauumae basalt, disposed in heavy blocks separated by joints and bedding planes nearly all at steep angles. Apparently the lava flow solidified in thick masses on a fairly steep slope, and the contraction joints, roughly normal to the layers, were also steep to the horizontal. The hardness of the basalt to percussion drills and the discordance between the natural separation planes and either the face, walls, or roof of the tunnel made the rock relatively troublesome both to excavate and to support.

At about 580 feet, after more cinders and a soil layer, the tunnel encountered the Koolau formation in a steep cliff face representing the east wall of Palolo Valley. From this point the tunnel passed through a short section of Koolau lava flows and thence through soil, Mauumae cinders, and flow lava in several more alternations, indicating ridges and hollows in the old surface of the Koolau rock on which the Mauumae volcanics were deposited (fig. 7).

Petrographically the Mauumae basalt is an olivine-augite porphyry, with conspicuous zoned augites in hourglass form and often in large clusters near an olivine crystal. The groundmass consists of augite, nepheline, and magnetite (plate XVIII).

KAAU BASALT AND TUFF

The Kaau volcanic rocks were erupted from Kaau Crater, near the crest of the Koolau Range on the leeward side and lying between the two branches of Palolo Valley. The crater is at present a flat-bottomed depression, 1,600 feet in diameter, with an outlet at about 1,575 feet into a small branch of Waiomao Stream which falls steeply 475 feet to the main stream. Koolau lava flows are exposed around most of the crater wall and only a few remnants of the Kaau basalt are found on the inside wall or top of the rim.

From the distribution of the Kaau basalt flows it is

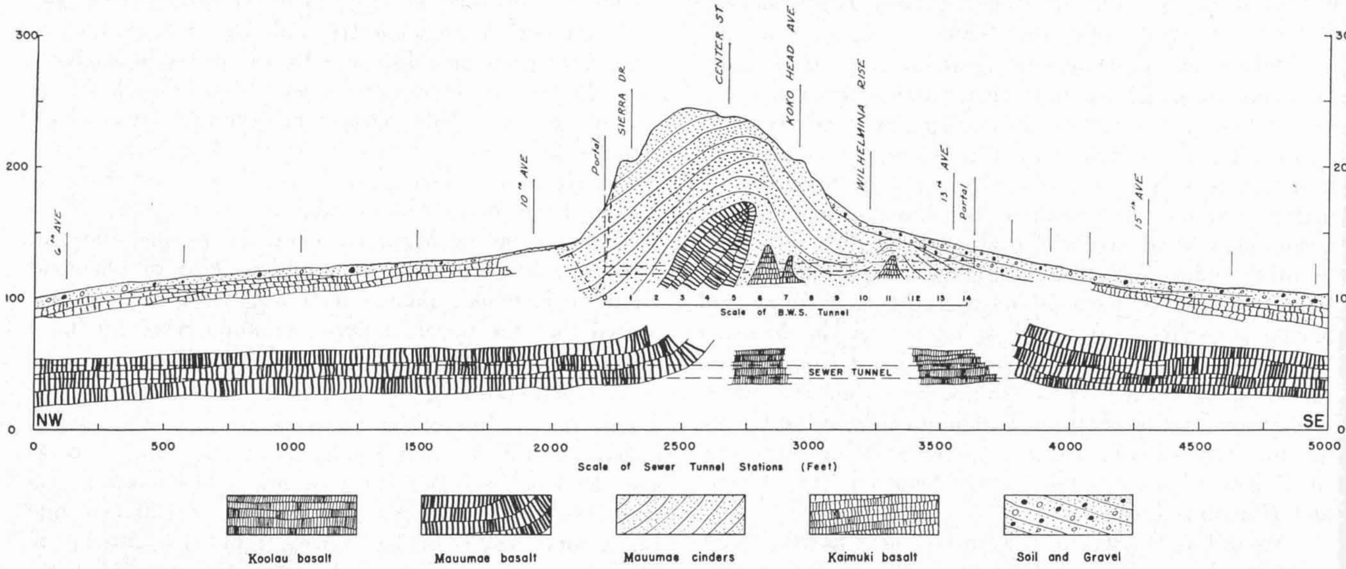

FIGURE 7. Geologic section along Keanu Street, one block inland from Waialae Avenue. Based chiefly on the water-main tunnel of the Board of Water Supply at approximately 120 feet elevation and the sewer tunnel at 40 feet elevation, interpreted in the light of available surface data. The highest peak and central vent of Puu Mauumae are 600 feet inland, back of the line of the section, and the mass of Mauumae cinders, erupted after the extrusion of large amounts of basalt that underlie the Kaimuki lava, surmounts the lower end of the Kapahulu spur of Koolau basalt adjacent to Palolo Valley.

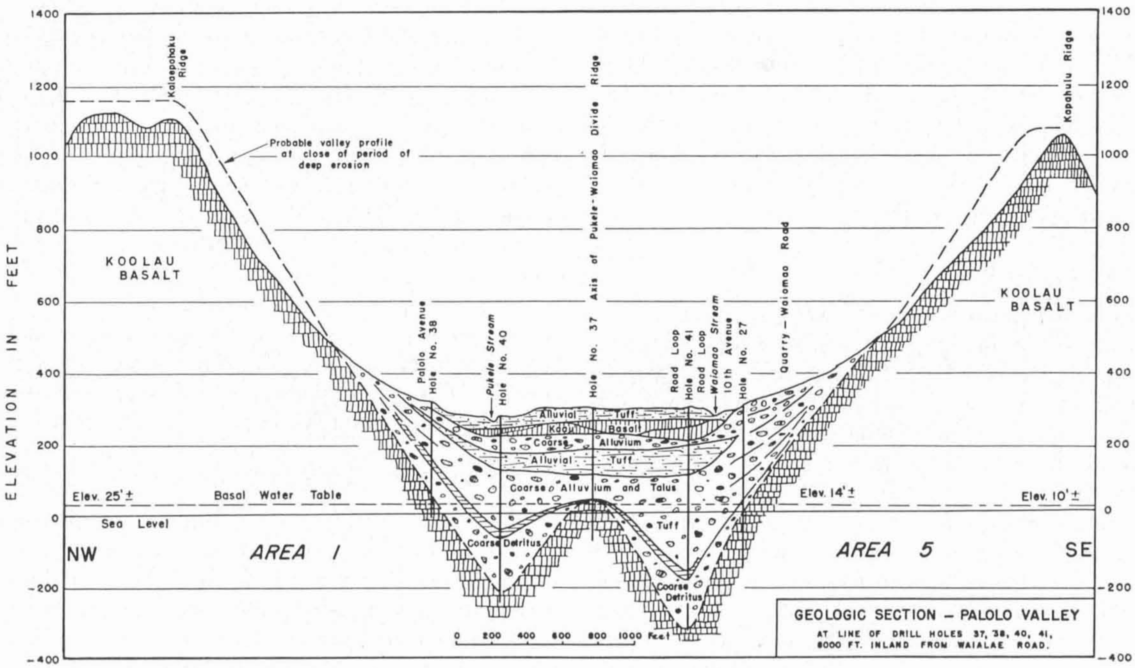

FIGURE 8. Geologic section, Palolo Valley at ca. 8,000 feet inland from Waialae Avenue. The section of the valley bottom is based on diamond drill holes 27, 37, 38, 40, and 41 and the general areal geology of the vicinity. This valley is the barrier between artesian areas 5 and 1, and the elevation of the basal water table in an orderly slope from around 25 feet on the northwest to about 14 feet on the southeast indicates clearly the resistance to ground-water movement caused by the relatively impervious valley fill.

clear that both Waiomao and Pukele Valleys and their branches had already been eroded before the Kaau Crater became active, since the lava streams poured down at least three channels toward the southwest and cooled in these channels and in the main valley of Palolo. This lava was extruded onto a dissected surface so that it formed fairly thick masses in channels or in pools where its flow was obstructed. Hence, it is commonly more massive, more homogeneous, more dense, and less marked by flow structures, vesicular crusts, aa layers, scoria mounds, and the like, than is the Koolau basalt.

The lower Kaau basalt is found at various places in the channel of Pukele Stream between the elevations of 650 and 250 feet. It rests unconformably on weathered Koolau lava and old alluvium in several places and is overlain by Kaau tuff and tuffaceous alluvium. At one point in the east bank of Pukele Stream at 550 feet, both the upper and lower flows are present, separated by about 10 feet of tuff. The eastern branch of Pukele Stream, which heads at the south rim of Kaau Crater, is floored for about 3,500 feet with a thin but nearly continuous remnant of Kaau basalt. This was probably placed by the upper or later flow since this basalt appears to overlie the Kaau tuff at its lower end.

A mass of Kaau basalt 10 to 30 feet thick lies in the east wall of Waiomao Valley for about 1,200 feet near the end of the road and is probably part of the later flow. The basalt is here overlain by alluvial tuff, but in drill holes 37, 40, and 41 what appears to be the same basalt overlies the main mass of Kaau tuff. The deepest Kaau basalt revealed by drilling is about 200 feet above sea level, but the ancient valley was cut to over 300 feet below present sea level near 10th Avenue at the Waiomao bridge (fig. 8). The contours on the base of the caprock as compiled by Palmer (1927) indicate that the floor of the Palolo Valley may have stood at 300 or more feet below present sea level west of the present Kaimuki pump station. This is consistent with the depth revealed at Waiomao bridge.

At one point in the east bank of Waiomao channel, the basalt rests on weathered gravel and this in turn on weathered Koolau basalt. The contact dips southeastward, suggesting that the axis of the former valley lies southeast of the present channel. In Waiomao Valley, above the end of the road, large, rounded blocks of Kaau basalt can be found in the channel, and such boulders are also found in outcrops of intermediate alluvium in the same valley. The presence of remnants of the Kaau flow in the minor valley extending seaward from the Kaau rim west of Waiomao Valley shows that the Kaau lava must at least once have welled up in the crater to the elevation of 1,650 feet and flowed by three routes toward the sea. Kaau basalt has been found at two points on the crest of the ridge which forms the west wall of Waiomao Valley, and there is good reason to believe that the Kaau basalt in lower Waiomao Valley spilled over the wall from this ridge. No evidence has been found to show that Kaau basalt ever flowed out of the crater directly into Waiomao channel, but at various points large boulders of it are found in gravel formations in the valley bottom. Though most of the accessible rim of the crater is formed of Koolau basalt, blocks of Kaau basalt have been found on the inner rim to elevations of about 1,650 feet or somewhat over 50 feet above the present outlet.

In thin section, under the petrographic microscope, the Kaau basalt shows a conspicuously porphyritic texture, with chunky olivine crystals ranging up to a millimeter or more in diameter. There is no feldspar in the rock and, because of the lack of elongated laths, the matrix is a rather equigranular mosaic of compact grains of augite, nepheline, and large or smaller amounts of melilite. In a few instances there are enough elongated laths of melilite to give the aspect of elongated slits to the matrix. The grain size is commonly 1/20 to 1/10 millimeter. The augite tends to occur in irregular, somewhat elongated masses adjacent to the olivine phenocrysts. The more equigranular part of the matrix is formed by nepheline and magnetite. Magnetite is present in all sections and is very abundant in some. The dissemination of the fine-grained magnetite throughout the clear phenocrysts and groundmass produces a dusted, gray appearance, like a charcoal sketch, which is very characteristic, especially in sections of the Waiomao branch of the Kaau flow. Most of the specimens are practically unweathered; in a few, the olivine is altered to the magnesium silicate, antigorite. In a few others, the olivine is marginally altered to iddingsite.

The primary Kaau tuff consists of layers of cemented cinder and ash particles ranging, in general, from 2 to 10 millimeters in diameter. In some places it is gray, slightly porous, and moderately hard. In others, it is red or brown, contains more palagonitized glass, and is commonly weathered to soft, compact, clay-like banks resembling the older alluvium. In some exposures of Kaau tuff there are pebbles and cobbles of weathered basalt which indicate alluvial origin. Much of the alluvial fill in Pukele and Waiomao Valleys which contains tuffaceous material is probably secondary alluvial tuff formed by erosion of the steep slopes soon after the eruption and by the consequent accumulation of juvenile cinders along with pebbles and other detritus in these thick alluvial trains in the valley bottoms.

In many places, beds of secondarily transported ash and cinder particles were accumulated without appreciable contamination by ordinary alluvial debris. Since much of the tuff is weathered and bedding is not well shown in outcrops, it is impossible in many instances to distinguish between the aeriform bedding and the alluvial bedding where the material consists almost wholly of volcanic detritus from practically contemporaneous eruptions. In spite of the massive, nearly structureless character of much of the tuff, the writer has not seen any parts which he would identify as mud-flow deposits as reported by Stearns and Vaksvik (1935, pp. 125–126). It is believed that if true mud-flow deposits were present, the grosser structures, unconformable overlaps, and the like, due to mass movement, would be easily distinguishable. Moreover, such mass movement in a district of steep slopes would strongly tend to involve underlying blocks, boulders, logs, sticks, and the like and thus would leave distinctive evidence of such movement. Even the coarser parts of the older and intermediate alluvium found in this valley show orderly and characteristic alluvial bedding and no valid indication of mud-flow deposition was found. The presence of large boulders and of thick, wedge-like deposits is not regarded as valid proof of mud-flow behavior.

The following sequence of events is suggested as a possible explanation of the crater and its products. The eruption possibly started when a magma column worked its way toward the surface along the rift line indicated by the vents trending from Diamond Head to Kaau. The lava may have reached the surface at an elevation of perhaps 1,800 feet, or it may merely have stoped its way nearly to that level. In either event, it is suggested that extrusion of the earlier Pukele lava flow may have taken place from minor fissure vents in this valley, releasing the pressure in the main lava column under Kaau and leading to its collapse and the funnel-shaped engulfment.

Events at Kilauea in 1924 showed that such engulfment and retreat may be accompanied by violent explosions, and it seems plausible that, under certain conditions, an explosive phase, possibly phreatically induced, might very well eject material preponderantly of juvenile origin. Whether the explosive phase was intimately and spasmodically connected with the cascading and plugging action of engulfed detritus, as at Kilauea in 1924, or represented an explosive introduction to the advance of magma which filled the crater lake and led by overflow to the second and upper lava flow, is not certain. Lack of beds of accidental detritus lends support to the latter interpretation. That the second lava invasion formed a lake and finally overflowed its rim is clearly indicated. Quite likely the retreat of the lava after its second rise was followed by a sufficient additional engulfment so that much of the lava ledge which commonly surrounds such a lake was undermined and carried into the bottom of the crater, where it has been buried.

The remarkable symmetry of the Kaau Crater indicates that a central vent was well established by the time the lava lake was formed and the second lava flow poured into Pukele Valley. Stearns (Stearns and Vaksvik, 1935, p. 125) says that this circular crater was formed by the explosions which "blasted a vent through the Koolau dome" at this point. It seems more probable that the Kaau Crater was given its present symmetrical form by a funnel-shaped engulfment, perhaps due to withdrawal of a lava column, similar to the action which took place at Kilauea in 1924. It was essentially a pit crater (Wentworth and Macdonald, in press). No accumulations of explosion breccia, or of tuff containing angular accidental or accessory constituents, similar to much of the Keanakakoi formation at Kilauea, have been found. Since even the lithic, largely accessory or accidental, pyroclastic beds at Kilauea probably resulted from explosions related to engulfment rather than to an aggressive blasting of the primary opening, it is reasonable to suppose that had the larger part of the crater been formed in such a manner, sufficient amounts of explosion breccia would have been thrown out as to leave some identifiable record.

Kaau Crater was more likely formed by a combined process of melting and of collapse, whereby a nearly circular pit was produced. This pit is cut through normal Koolau structure and was originally a deep funnel, its present flat-bottomed form being due to aggradation of the floor by sedimentary wash. At any rate, the explosions produced only essential ash and cinders which were flung out to form a mantle over several square miles of the surrounding slope of the Koolau Range. They probably reached a thickness of 10 feet as much as 2 or 3 miles away, including the eastern part of the head of Manoa Valley. After this explosive phase, the crater was evidently occupied by a lava lake which rose to an elevation of at least 1,650 feet, to leave Kaau basalt ledges in the inner walls of the crater and to permit the overflow of the lava into the head of the eastern branch of Pukele Valley through a saddle which now stands at slightly over 1,600 feet.

Evidence is lacking for a clear dictum as to the relative ages of the Kaau and Mauumae formations. Correlation of the late basalt in the Kapahulu quarry with the Mauumae flows removes the evidence on which Stearns (Stearns and Vaksvik, 1935, p. 68) at first considered the Kaau flows to be the older. Both the Kaau and Mauumae eruptions took place when the topography was more deeply cut than now and when the sea stood below present sea level. The structure of the Palolo Valley fill suggests that Palolo Valley may have been partly blocked by Mauumae lava.

DIAMOND HEAD TUFF

In Kapahulu quarry the Diamond Head tuff lies under Kaimuki basalt and on weathered alluvial gravel, the latter lying in turn on nepheline basalt which is probably from the Mauumae vent. The weathering of the gravel suggests that the Mauumae basalt is substantially older than the Diamond Head tuff. The Kaau basalt and ash were probably erupted during either the Kaena or Laie stands of the sea and a considerable time prior to the Waipio and Waimanalo stands when the Diamond Head, Kaimuki, and Black Point volcanic formations were placed (Stearns and Vaksvik, 1935, p. 68).

Palolo Valley, from 100 feet below to 200 feet above sea level, was filled by tuffaceous alluvium soon after the Kaau explosive phase. This suggests that the lower end of the valley was already obstructed by a part of the Kaimuki dome, presumably that part which is composed of Mauumae basalt. Thus it is possible that the earlier Mauumae eruption, as set forth above, antedated the Kaau eruptions. The Diamond Head, Black Point, and Kaimuki eruptions came later. Of the latter series the Diamond Head tuff is the older, though all may be the products of a nearly contemporaneous series of eruptions. The petrology, form, and origin of Diamond Head have been discussed elsewhere in considerable detail (Wentworth, 1926, pp. 32–55). Diamond Head is the best-known and the most characteristic of the saucer-shaped tuff craters of southeast Oahu. It stands on a base of reef limestone, 200 to 300 feet below sea level, which slopes gently to seaward. According to the log of the James Campbell well (old No. 1, present No. 18), the surface of the Koolau basalt, possibly truncated by marine erosion, lies about 1,200 feet below sea level under the Diamond Head mass, with reef limestone and terrigenous formations intervening.

The circular rim of Diamond Head is nearly 4,000 feet in diameter, and the mass consists of indipping and outdipping beds of compact, palagonite tuff. It has no known connection with the rocks of the Koolau Range, and, since it stands in a district of about 22 inches of annual rainfall, it is unimportant as a water-bearing or water-restraining formation. Like most of the other tuff craters of southeast Oahu, the Diamond Head mass thins very rapidly from a maximum thickness of about 1,000 feet at the highest point of the rim to an average of not over 300 feet at 1,000 feet from the rim and less than 10 feet at 1.4 miles from the rim. The tuff of Diamond Head contains basaltic bombs, accidental masses of reef rock, and blocks of older basalt torn from the walls of the vent. The finer matrix and most of the formation consists of volcanic ash particles which were originally basaltic glass but are now altered on the surface and around the margins of the vesicles to the mineraloid known as palagonite. This is a characteristic alteration product, produced by the hydration of glass particles, which imparts the characteristic yellow, red, and brown colors to the tuff of all the secondary craters of southeast Oahu. The alteration apparently takes place from the surface inward and in proportion to the amount of exposed surface. Hence the effect is most pronounced in the finer materials where a large fraction has been altered to the palagonitic condition. On the other hand, in some coarser layers of cinders, the individual glass particles are only slightly changed on the surfaces and thin edges and remain chiefly in the condition of clear glass.

The bedding of the Diamond Head tuff is due to the progressive mantling of debris deposited from the air. The bedding is nearly parallel, but the beds thicken toward the zones of great accumulation. In some places, due to contemporaneous erosion, cutting of sea cliffs, or the slumping of the newly deposited ash, there are unconformable contacts of newer beds on older, and in others there is a slight cross-bedding which appears to be due to action of the wind. The bedding in the tuff is chiefly expressed by zones of coarser particles, lapilli, or bombs due to pulsations in the eruption. However, these coarser fragments are embedded in a matrix of finer ash particles which probably fell continuously from the air.

The central bowl of Diamond Head is mantled by secondary, colluvial deposits of fine and medium detritus somewhat cemented by calcium carbonate. No field evidence to show the structure of the vent has been found. Erosion has stripped a few beds off the slopes in some places near the crest, and a few large ravines are cut in the outer slopes of the cone (plate XIX).

BLACK POINT BASALT

The Black Point basalt covers an area of about 40 acres southeast of Diamond Head and forms a projecting headland of the coast. This projection, known as Black Point, is of tabular form with fairly steep slopes on the east, south, and southwest sides. An area of about 5 acres rises above the 100-foot contour, and the saddle between this Black Point plateau and Diamond Head, underlain by tuff and reef rock, is 65 feet above sea level.

The basalt terrane is completely isolated from the present cone of Diamond Head, though it is probable that the original slope of the cone was continuous from the surface of the tuff which underlies the basalt northwestward to the steeper slope and rim of the crater. The basalt flow covers the entire top of the plateau above the elevation of about 85 feet and extends down the northeastern slope to an elevation of 25 feet. It reaches the sea in the coastal angle at the west in a thick mass, and another tongue extends down the southeast slope to form the shore for about 800 feet at the southeastern extremity of Black Point. A small remnant of basalt crops out at sea level east of the eastern coastal indentation. Along much of the southwestern side are more or less disturbed remnants of the basalt, suggesting that the basalt veneered this slope and has since been extensively undermined.

At several points around the southern and southwestern margin of the plateau the basalt flow, which is 15 to 25 feet thick, lies on little-eroded Diamond Head tuff at the elevation of about 85 feet. The upper layers of the tuff are marked by a close-spaced jointing induced by the heat of the superposed basalt flow. Along the southwest slope, below this contact, is a heavy talus of basalt blocks. At the south point, tuff is continuously exposed from the contact down to water level. East of this place, basalt lies on what appears to be a wave-cut bench a few feet above sea level.

The westernmost part of the basalt is a thick mass forming a coastal cliff about 15 feet high and 100 feet long south of the coastal re-entrant. A short distance farther south there are discontinous remnants of a dike, extending out to sea, which are similar to the main flow. This dike is intruded into a reef-rock mass which rises about 8 feet above sea level. The reef-rock formation is free from cobbles of either tuff or basalt and evidently antedates the formation of Diamond Head or the Black Point flow. Above the Black Point flow in some places, and lying on accumulations of basalt boulders from the flow in others, is a calcareous beach limestone which contains abundant cobbles of Black Point basalt and of Diamond Head tuff. The lower calcareous reef formation is probably of Kaena age and the beach rock of Waimanalo age. The Diamond Head and Black Point volcanic eruptions have been assigned to the Waipio low stand of the sea, which appears valid insofar as the supposed sequence of sea-level shifts is correct (Stearns and Vaksvik, 1935, pp. 140–143). The Black Point flow is a black, massive, somewhat vesicular basalt which contains olivine and plagioclase feldspar. It resembles many of the basalts of the Honolulu series in megascopic appearance but is akin to the Kaimuki basalt in its lack of the mineral nepheline. The general petrographic character has been described elsewhere (Winchell, 1947, pp. 14–15, 29).

The Black Point basalt cannot be correlated with

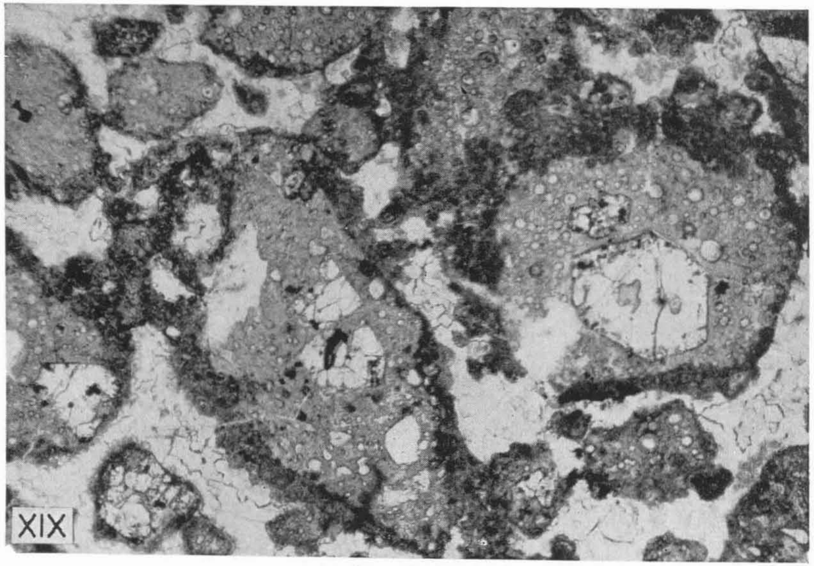

PLATE XIX. Photomicrograph of Diamond Head tuff, showing several of the component pellets of basaltic glass (diameters ca. 1.0 millimeter) with the margins altered to palagonite. The glass is light green and the palagonite margins lemon yellow. Surrounding the pellets are areas of cementing calcite and in them are olivine crystals and vesicles representing gas bubbles when the lava was a liquid.

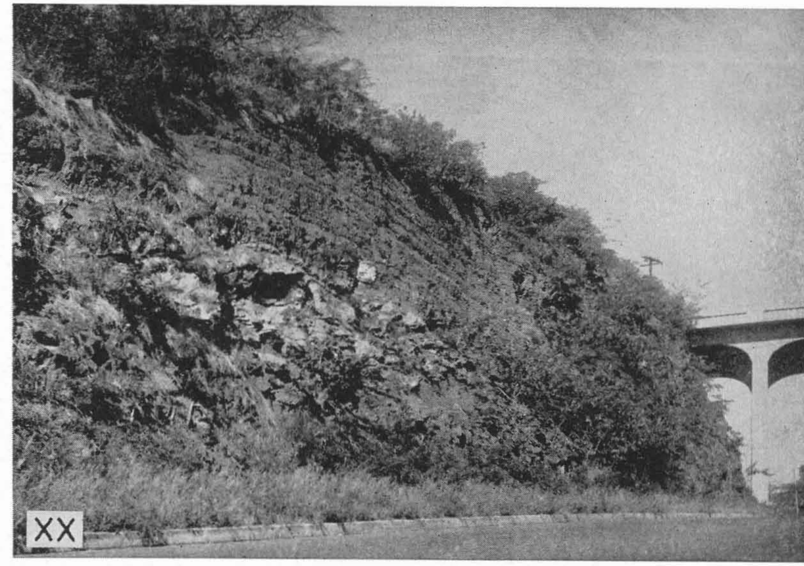

PLATE XX. Contact of Punchbowl tuff (upper, banded) on Koolau basalt (irregular, blocky) in bank of Auwaiolimu Drive, southeast of Tantalus Drive bridge in Punchbowl saddle.

PLATE XXI. Tantalus black sand and cinders in pipe trench on Kinau Street. The white bands and nodules are lime carbonate deposited in certain layers and in root molds, burrows, and other openings. Above the black sand in this area is an irregular layer of brown soil.

PLATE XXII. Makuku Crater, from the west wall of Nuuanu Valley, seaward from the Upside-Down Fall, at about 1,800 feet. Skyline at the middle distance is Pauoa Flats, with Tantalus on the right. In the left lowland is Nuuanu Reservoir No. 4. This crater marks a vent which has been the source of many lava flows of

Diamond Head or ascribed to the same eruption because of its distinct petrographic features, the Diamond Head tuff belonging to the nepheline-bearing series. There is no evidence of surface connection between Kaimuki cone and the Black Point flow, and, because such a connecting mass would be very likely to survive in places, it is unlikely there ever was such a connection. It is more probable that the Black Point flow was erupted from a fissure vent, related to the existing dikes, contemporaneously with one of the eruptions by which the Kaimuki cone was built.

KAIMUKI BASALT

The Kaimuki basalt forms a typical lava dome, the apex of which is marked by an elongated, undrained depression about 30 feet deep and 900 by 1,500 feet in horizontal dimensions. The highest point of the rim reaches 302 feet above sea level. The Kaimuki dome has a north-south diameter between the Koolau margin and Diamond Head of about a mile. In the east-west direction, where the slopes merge with lower parts of the adjacent coastal plain, the diameter is about 1½ miles. Adjacent to Palolo and Waialae Valleys the Kaimuki basalt probably extends under the alluvial surface and its component flows are interbedded with the upper alluvium.

The Kaimuki basalt in places consists of fairly thick, massive lava flows separated by cooling cracks into irregular, polyhedral blocks. Near the west margin at Kapahulu quarry, where the basalt rests on Diamond Head tuff, it is 5 to 8 feet in thickness, and similar thicknesses are shown at various other places around the margin. The rock is olivine basalt, usually fresh and black on fractured surfaces. Near the vent, and especially in the high part of the rim which is exposed at the Kaimuki Fire Station, the Kaimuki basalt is composed largely of very thin, frothy layers from 2 inches to a foot thick. Small amounts of cinders and ash are found inside the depression. A notably red soil a few inches to several feet thick has formed by weathering from the Kaimuki basalt, and the transition downward through partly weathered rock to compact, joint-bounded flow blocks is well shown in many excavations on the dome.

The most recent Kaimuki flows, around the west foot of the dome, are undoubtedly younger than Diamond Head since the basalt lies some 5 to 8 feet thick on Diamond Head tuff in the Kapahulu quarry. No great amount of erosion of Diamond Head had apparently occurred before the placement of the basalt, so that the basalt may be nearly contemporaneous with the tuff.

At the Liliuokalani School grounds, Kaimuki basalt was penetrated in a drill hole to a depth of about 50 feet below the surface, reaching the elevation of 125 feet above sea level. From this point to 25 feet below sea level the hole penetrated nepheline basalt believed to be from the Mauumae vent. Unfortunately the hole did not reach the base of the latter basalt. It is believed that the wave-cut surface of the Koolau basalt may lie 50 to 100 feet below sea level. The seaward slope of this eroded surface, as shown in the log of the James Campbell well, would carry it to a depth of 200 to 250 feet below sea level under the center of the Kaimuki dome. Diamond Head probably rests on a reef-rock floor at 200 to 300 feet below sea level. Whether the reef rock which lies under part or all of Diamond Head at this depth extends inland on the Koolau pavement under Kaimuki and abuts against the wave-cut margin of the Koolau Range, is not known. The Diamond Head tuff near the center of the Kaimuki dome is probably not over 10 to 20 feet thick and thus may lie either on reef rock, on marine sediments, or on the Koolau pavement at 100 to 200 feet below sea level. Hence the Kaimuki dome near its center may have a thickness from 400 to 550 feet (fig. 9).

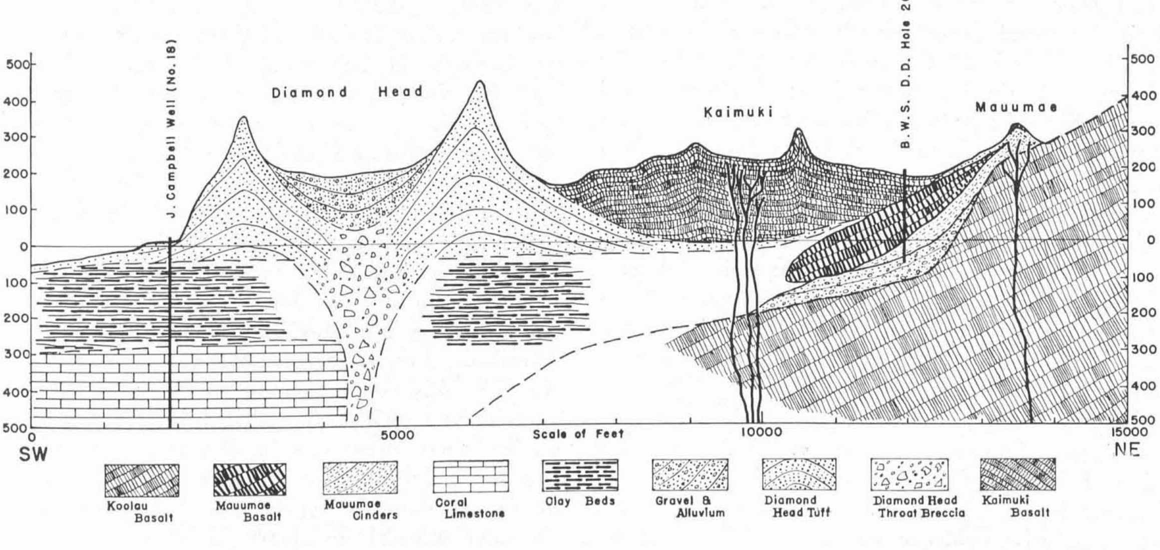

FIGURE 9. Geologic section, Diamond Head to Mauumae. Based on the general structures of the Koolau formation and the Diamond Head, Kaimuki, and Mauumae cones, and on the logs of the James Campbell Well and diamond drill hole 20. The surface of the Koolau rock was reached by the Campbell Well at about −1,163 feet, but was not reached, owing to drilling difficulties, in diamond drill hole 20. What is thought from other data to be the surface of the Koolau under Waialae Avenue is indicated.

At Black Point, at the time of formation of Diamond Head, there was evidently a reef mass extending some 6 to 8 feet above present sea level. This reef, extending in places to 25 feet above sea level, probably dates from the Kaena stand of the sea. It probably had not been formed at the time of the earlier Mauumae eruptions, which may have taken place earlier in Kaena time. Somewhat later, according to Stearns, during the Waipio low stand of the sea, the Kaimuki lava was poured out (Stearns and Vaksvik, 1935, p. 139).

In thin section, the Kaimuki basalt adheres closely to a typical structure and composition. It is much coarser in grain than either the Koolau or the Kaau, with conspicuous phenocrysts of olivine and of plagioclase feldspar. The matrix is so coarse as to somewhat obscure the porphyritic texture, and it appears as a mosaic of subequal amounts of olivine, augite, plagioclase feldspar (usually labradorite near andesine), and magnetite. The augite crystals are mostly stout and chunky. The feldspar is more scattered and relatively less abundant than in the Koolau basalts. Magnetite occurs in large, euhedral, quadrangular grains and in aggregates of these. Olivine commonly appears in grains ranging up to 2 or 3 millimeters in diameter. The chief variation in the character of the rock is in the amount and size of the feldspar crystals.

DIAMOND HEAD BLACK ASH

At various places near Black Point and in the saddle between Diamond Head and Black Point there is a mass of fine-grained black sand, ranging in thickness from a few inches to about 5 feet. The black sand in some places is only slightly laminated and has a structure apparently due to primary volcanic deposition from the air. In other places it shows eolian cross-bedding. Locally it contains grains of calcareous sand, but mostly it is composed wholly of glass, olivine, and other minerals normal to the pyroclastic formations of the Honolulu series. It overlies a part of the Diamond Head talus breccia and in turn is overlain by high beds of the same formation. On the Black Point coast the exposed beds of this black sand overlie a post-Black Point beach limestone so as to indicate that these particular beds are considerably younger than the Black Point lava.

This sand formation has long been regarded as a black ash, the result of explosive expulsion of basaltic lava, and was so considered by the present writer (Wentworth, 1926, p. 45). In 1935, Stearns questioned this interpretation and described the black sand as a dune sand, blown up from a shore on which basalt and tuff were being abraded (Stearns and Vaksvik, 1935, p. 142).

In 1937, the formation was re-examined by the writer in the field and abundant evidence was found to show that this is indeed a primary volcanic ash produced by explosive eruption and not a dune sand due to abrasion. The most conclusive evidence was afforded by a persistent 1-inch layer of volcanic pisolites formed in rain drops at the time of the eruption (Wentworth, 1937, pp. 91–103). The exact vent from which this ash came is not known, but its identity as a pyroclastic event, dated sometime after the Black Point and the Diamond Head eruptions, is established.

ROCKY HILL VOLCANICS

Rocky Hill, on Punahou School grounds, is the highest point of a small crater now partly buried in later lava flows and the pyroclastics from Sugarloaf, Tantalus, and Roundtop. According to Stearns (Stearns and Vaksvik, 1935, pp. 101–103) other craters belonging to the Rocky Hill group lie, respectively: 1,000 feet southeast, 2,000 feet east, 1,800 feet northeast, and 4,200 feet northeast. The last is only a small kipuka projecting above the Sugarloaf lava flow. Lack of outcrops in this settled area makes it difficult to determine relationships, and no practicable method has been found for separating these pyroclastics from those belonging to the Tantalus–Roundtop system, and no differentiation has been attempted in mapping.

A flow appears to have issued from the southwest side of Rocky Hill at about 200 feet elevation and extends seaward at least several hundred feet. Differentiation of this flow from the surficial valley-filling flows farther eastward is very uncertain, and they have been mapped together. Both the Rocky Hill flow and the main, valley-filling flows are rich in nepheline.

Petrographic examination shows that the Rocky Hill flow may be distinguishable from the Sugarloaf flow on the basis of the ratio of pyroxene to melilite in the groundmass. Using this criterion, the boundary between the Rocky Hill flow and the Sugarloaf flow appears to lie about on the line forming the southwesterly continuation of McKinley Street.

TANTALUS–SUGARLOAF VOLCANICS

Loose, generally unconsolidated cinders, consisting of partly coalescent glassy shards with phenocrysts of olivine, magnetite, and melilite, cover Tantalus, Sugarloaf, and Roundtop, as well as the eastern slopes of Rocky Hill. No basis for subdivision of the formation—for distinguishing between cinders from the several craters of the Tantalus–Sugarloaf group, or from Rocky Hill—has been found. The cinders form a highly permeable and porous cap affording favorable intake conditions for rain water. Most of this intake probably does not lead to the basal water system but to perched water bodies that in part return as surface springs.

In one of the minor valleys draining the main Tantalus cone, a dike of rock crops out, similar in every respect to the Tantalus–Pauoa–Manoa lavas about to be described. This is presumably one of the dike feeders to the Tantalus vents. Unless many more can be shown to exist beneath the Tantalus, Sugarloaf, and Roundtop masses, these dikes can hardly be considered to be of hydrologic significance. The dike rock is somewhat denser in texture than the typical extrusive phase but contains the same minerals in about the same proportions as the extrusive rock.

Cinder beds and lavas from Tantalus have largely filled Pauoa Valley, blocking it opposite the Tantalus vent and reversing the head drainage. This drainage has been diverted into Aihualama Stream, the westernmost tributary of Manoa Stream. There was also a Makiki lava flow, now almost entirely removed by erosion, but indicated by the presence of small remnants and by the dike feeder in the western branch. The most important flow from the Tantalus–Sugarloaf group is the great valley-filling flow that moved down the west side of Manoa Valley from a vent somewhere in the eastern slopes of Sugarloaf. This flow partly buried a number of cones and volcanics belonging to the Rocky Hill group. The flow was predominantly, if not entirely, aa, as shown by the remarkably flat upper surface, a feature to be noted in many places on the floor of Manoa Valley. No doubt this surface has been partly levelled by deposition of sediments, as on a flood plain, and by deposition of cinders from the later eruptions.

This flow formed a barrier across Manoa Valley and thence moved down the eastern side of the valley skirting the Rocky Hill craters and forcing Manoa Stream eastward to its present position. The flow underlies nearly a square mile in the Moiliili area, including the quarry of that name. About 8 million cubic yards of rock have been taken out of that quarry, setting a standard of quality for commercial rock which has been difficult for quarries in other formations to meet.

Petrographically, the Sugarloaf flow is a melilite-nepheline basalt. Complete lack of any detectable feldspar removes it from the group more strictly known by some as basalt. Several minerals occur as phenocrysts. Of these olivine is the most prominent. Its optical properties show that its composition is essentially the same as that of the Koolau olivine, namely, 85 per cent forsterite, 15 per cent fayalite. Augite phenocrysts occur in a few specimens but are not as common as in some other Honolulu lavas. The augite is strongly zoned and shows conspicuous hourglass structures. This hourglass structure is not known in augite crystals from the Koolau series.

Magnetite, usually in small, typical octahedral-dodecahedral forms and sometimes strung out together in lines, is one of the earliest minerals to crystallize. Its crystallization period appears to extend well into the post-extrusion period, however. Glassy material in the cinders contains considerable amounts of very finely divided magnetite grains which sometimes render the shards opaque, even in thin section. Melilite platelets form a very considerable proportion of the Sugarloaf lava. They are mostly phenocrystic, as shown by the fact that they occur also in the glassy cinder material of the pyroclastic deposits, but there is evidence that they continue their growth after the extrusion of the lava. In some specimens melilite forms such a large part of the rock that its lath-like sections arranged in all orientations produce a felty texture, with nepheline and occasional grains of hauynite and other minerals forming the surrounding intersertal material. Melilite usually shows a strong development of "peg structure," or lineation parallel to the c-axis, resulting from development of inclusions pointing inward from the basal pinacoid.

The minerals of the groundmass are nepheline, augite, hauynite, and apatite. Glassy material may sometimes be present. Augite in the groundmass is likely to be zoned in a manner similar to that of the phenocrystic augite. It is not abundant in the Sugarloaf flow. Hauynite forms brownish, clear, isotropic crystals in the Sugarloaf lava. Identification of the mineral is confirmed by microchemical tests. Apatite forms a small proportion of the rock—perhaps as much as 1 or 2 per cent. In Moiliili Quarry it is much more generally developed in the pegmatitoid phases of the rocks and may reach 10 or 15 per cent concentration in certain cavity linings. Since relatively insignificant amounts, if any, of the water taken from the artesian basin can have entered the basin through channels even remotely connected with these apatite concentrations, it seems reasonable to suppose that the amount of fluorine contributed to the water from this otherwise rich source (apatite) must be quite negligible.

Tantalus Crater is marked by three peaks on a rim about 1,400 feet in diameter, each rising slightly above the 2,000-foot contour and the whole surrounding an elongate hollow with its floor at about 1,800 feet. The Tantalus cone stands almost precisely on the Koolau spur between Manoa and Pauoa Valleys, and its lower margin takes on forms imposed by the underlying topography. The eastern slope of Tantalus continues upward from the steep west wall of Manoa Valley, and the northwestern slope of Tantalus is mantled over the southeast wall of Pauoa Valley.

The latter, originally one of the smaller valleys and lying on the windward side of Tantalus, has been profoundly altered by the fill of Tantalus cinders. Nearly straight north of the vent, the fill of cinders formed a topographic divide across Pauoa Valley, throwing the drainage of the ash-filled head of Pauoa over the ridge into Manoa along the course of the present Aihualama Valley. From the cinder divide which is now the head of Pauoa Valley, for about three quarters of a mile seaward, the valley is filled 100 to 300 feet deep with cemented cinders on which a palmate system of head branches has been developed. Because of the manner of erosion of the porous cinders (Wentworth, 1938, pp. 64–65), these small branches have carved some extraordinarily narrow and deep canyons and some very steep headwalls. On the eastern wall of Pauoa Valley, patches of cinders continue nearly to the seaward end of the Koolau spur, alternating with the parts of the wall from which they have been stripped. The partly weathered cinder formation has been extensively dug in this area for fill and garden soil. On the top of the Tantalus spur of the Koolau Range, leeward from the vent, and in adjacent valleys of the Makiki system, Tantalus cinders form a mantle which in some places is probably 50 or 75 feet thick. In many others this cover is thin enough so that the underlying weathered Koolau rock or residuum is exposed in 10-foot road cuts.

Driblet material, in masses up to 6 inches across, together with lava balls and bombs, is found in parts of the cone near the vent, but much of the cone is composed of cinder lapilli in the 4- to 16-millimeter grades. Strikingly uniform mantle bedding is characteristic of the black sand and cinders, both near the vent and 1 to 2 miles away on Punchbowl and beyond.

The Tantalus and Sugarloaf eruptions were responsible for the widespread cover of fine black cinder and sand which is so conspicuous in the Makiki area of Honolulu between Punchbowl and Punahou Street and extending nearly or quite to the coast (plate XXI). In some places the black sand is 10 feet or more in thickness, and in most of the area it is the most important part of all shallow excavations. Many drainpipes were discharged into it in the early days of Honolulu's growth and a few such pipes probably remain in operation. When fresh, the cinder and black-sand particles appear as black iridescent bits of glass in the form of vesicular ribbons or droplets. Under the microscope, the glass is transparent, light green, and marked by microlites and bubbles. The Tantalus eruption appears to have been especially productive of magnetite crystals which have become freed from the glass. Fine black magnetite sand, possibly with some ilmenite, is especially noticeable in roadside rills in the vicinity of Tantalus.

Nearer to the vent there are beds composed chiefly of small balls, ¼ to 2 inches across and occasionally larger. These balls may in part be due to growth within the throat of the vent, or to the accretion of finer dust around a single heavier nucleus in the atmosphere during flight, or finally to accretion (snowball fashion) by rolling on slopes after landing. Some possible light is thrown on this matter by the observed fact that in any given stratum of these ball beds, the size of the balls increases progressively upward. For example, in a bed 9 inches thick, the balls forming the base may average ¼ inch across and the size may increase very uniformly through the 9 inches to an average of perhaps ¾ inch. Both top and bottom of the bed are very distinct and may lie in contact with the bottom and top, respectively, of beds of similar range of coarseness. It is difficult, using any assumption in regard to expulsion mechanism or flight behavior, to explain such uniform increase of size, a condition quite the reverse of what would normally be expected. It is suggested that such a gradation may be due to progressive accumulation by rolling down a slope, the balls capable of reaching a given spot being in general only those enough larger than those just laid down to pass over the existing surface and increasing in size as a given layer is built up. These balls usually have a core of solidified lava or of more compact, heat-welded ash which is surrounded by less compact material taken up in the course of its growth.

In places the finer parts of the Tantalus pyroclastics are somewhat palagonitized, but for the most part they are bonded by compacting or are slightly lime-cemented so as to stand in vertical walls 5 to 20 feet high. The mechanical composition and porosity of a few samples are given elsewhere in this report.

The Tantalus basalt was extruded from the Tantalus vent during the eruptions which produced the cinder formations. The basalt overlies some of the cinder and underlies the later part of it. It is exposed in the edge of Pauoa Flats in the small alcove which Aihualama Stream has cut at the top of the Manoa wall. Here it lies on a thin layer of talus and alluvium above the surface of Koolau rock. Similar relationships are shown in the axis of Pauoa Valley at about 950 feet. The basalt is exposed at several points in the lower parts of branch channels of Pauoa Stream on the western base of Tantalus cone and also somewhat discontinuously down the channel of Pauoa Stream to the head of the lower valley flat. The form of the lower Pauoa valley flat indicates clearly that the basalt spreads across the floor and passes seaward to merge with Nuuanu basalt in the upper structure of the coastal plain. Tantalus basalt was indicated in various diamond drill holes in Pauoa Valley in the vicinity of Booth Spring as being up to 40 feet thick. Farther down the valley two flows appear with an interbedded lens of tuff. Under the basalt is 60 to 70 feet of somewhat cemented cinder tuff, lying on 5 to 30 feet of weathered detritus, which, in turn, lies on the Koolau rock.

Stearns has stated that the Tantalus basalt forms the barrier cutting off Pauoa Flats from the existing Pauoa Valley and that the Tantalus basalt was erupted toward the end of the Tantalus eruption (Stearns and Vaksvik, 1935, pp. 161–162). These statements do not seem to the present writer either quite consistent with each other or with the outcrops he has seen. It seems more likely that the extrusion of basalt was midway during the eruption and that the barrier had already been formed by accumulation of cinders in the narrow valley opposite the vent. In this case the basalt which lies under Pauoa Flats may be distinct from the basalt which lies between considerable thicknesses of cinder tuff in various parts of the east side and the axis of Pauoa Valley.

According to Winchell (1941, pp. 118–119), the Pauoa flow is unusual petrographically for its "high percentage of melilite plates, whose elongate sections give the rock a felty appearance in thin section. Flow texture is developed locally. Few augite or olivine phenocrysts, much pyroxene and nepheline, and considerable magnetite characterize the Pauoa flows."

PUNCHBOWL VOLCANICS

Punchbowl is a circular cone with an outer diameter of about 5,000 feet, a rim diameter of 1,800 feet, and rim elevations ranging between 400 and 500 feet. With the slightly larger crater Diamond Head, it is typical of the phreatic explosion cones in the Honolulu neighborhood. Practically all of its mass consists of tan to brown palagonite tuff. At its landward margin in the road cut of Auwaiolimu Drive the base of the tuff lies on Koolau basalt of the Tantalus spur at 270 feet above sea level (fig. 10 and plate XX). The tuff at this point is about 30 feet thick, and its outcrop ends practically at the saddle. On the seaward side, the base of the Punchbowl tuff in artesian well borings at the Beretania Pumping Station lies on a coral reef formation at about 60 feet below sea level.

From the relationship of the Punchbowl basalt to reef formations and the testimony of Wells 72 and 73 concerning the buried valley of Kanaha Stream, it seems most likely that Punchbowl was formed during the Waipio low stand of the sea (Stearns and Vaksvik, 1935, pp. 145–148). However, both the scale of positive and nega-

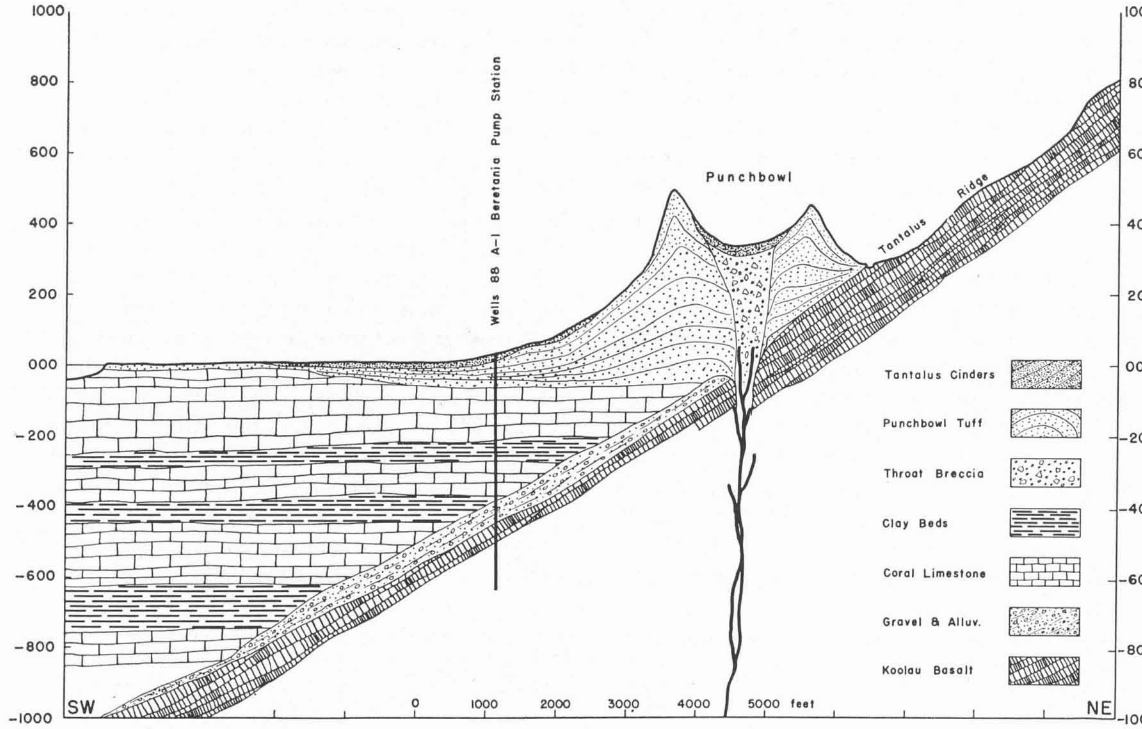

FIGURE 10. Geologic section through Punchbowl. Generalized from the fragmentary records of wells near the line of the section which follows Tantalus Ridge, Alapai Street, and Keawe Street approximately. Vertical scale exaggerated five times.

tive stands of the sea and the data from wells, terraces, or the like, are mostly based on single instances, or similarities of materials not yet absolutely traced.

These tentative conclusions are the best we have but only with much greater detail in subsurface explorations, if such are ever made possible, can we develop a more reliable set of age determinations.

Details of structure and petrography of Punchbowl have been discussed elsewhere (Wentworth, 1926, pp. 55–60; Stearns and Vaksvik, 1935, pp. 145–148). In the writer's earlier work in 1923, the black volcanic sand found in the crater bowl and around the outer slopes in places was attributed to a second eruption of Punchbowl, an erroneous interpretation which was challenged by Stearns, who found evidence adequate to show that the black sand is actually a part of the widespread black sand from the later Tantalus and Sugarloaf eruptions (plate XXI).

The only exposures of Punchbowl basalt are on the southern rim in and near the road loop and at the small gap in the east rim. It was first thought that the flow came from a point near the road loop, passed through the gap, and flowed some distance down the small branch of Kanaha Valley; but more detailed examination with better exposures and more brush cleared away indicates that no lava flow passed down the valley and that such blocks as are now in the valley were let down in the course of encroachment of the valley head across the rim. All the basalt found in place dips inward toward the center of the bowl and lies on the inner slope of the rim. It seems most likely that the lava was thrown or spilled on the inner slope of a part of the rim from a localized vent nearer the southeast side, but did not form a complete lake as some have thought (Stearns and Vaksvik, 1935, p. 148).

A dike was noted in the excavation of the Punchbowl Reservoir at Alapai and Crescent Streets, and a lava flow about 15 feet thick is revealed in the logs of Wells 88A to 88F at the Beretania Pumping Station. Most likely this flow came from the Punchbowl vent by way of the above-mentioned dike on the seaward slope of the cone (Stearns and Vaksvik, 1935, p. 148) (fig. 10).

The Punchbowl basalt is described by Winchell as a granular, porphyritic nepheline basalt with more olivine than augite phenocrysts. Both major constituents are in a groundmass made up of moderately abundant magnetite, dominant pyroxene with only a little less nepheline than pyroxene, and some accessory apatite. It falls in the prevailing group of the Honolulu series which is made up of nepheline and nepheline-melilite basalts (Winchell, 1941, pp. 106, 169).

NUUANU VOLCANICS

Late lava flows of the Honolulu series are extensively exposed in the floor of Nuuanu Valley from Reservoir No. 4 to the coastal plain. They are penetrated by various of the artesian wells of the Iwilei district (particularly Wells 114, 115, 116, and 118) at a depth of about 100 feet below sea level (plate XXIII and fig. 11). Along the floor of the upper valley, in highway cuts less than 15 feet deep, there is exposed an upper lava flow overlain by a few feet of clinker and underlain by cinders. This lava flow undoubtedly came from Makuku Cone, north of the west end of the dam at Reservoir No. 4 (plate XXII). Another much thicker flow is revealed at many points in the channel of Nuuanu Stream on the east side of Nuuanu Valley from the lower Luakaha fall seaward to Judd Street (plate XXIII). This flow has been designated as the lower flow by Stearns and is probably the same as the flow penetrated by artesian wells in the Iwilei district.

From the distribution of lava flows at the surface and from the depths of artesian wells and the behavior of artesian heads in areas east and west of Nuuanu Valley, there is much evidence that Nuuanu Valley was once cut much deeper and is filled with sedimentary and other formations. To furnish data bearing on possible water development in the valley, two rows of diamond drill holes were bored by the Board of Water Supply in 1934. The row farthest inland, consisting of nine holes (southeast to northwest, Nos. 7, 6, 10, 1, 2, 9, 4, 5, and 3), revealed a valley fill of slightly over 400 feet in thickness as shown in figure 11. The logs of these holes are on file, and cores are preserved. Because of the similarity of composition of lava flows, any interpretation of the section can be only approximate. The five holes which reached the ancient valley floor in Koolau rock all show a thick layer of deeply weathered, compact, mottled, impervious old alluvium 60 to 140 feet thick, lying directly on a moderately weathered Koolau rock surface. These holes are well distributed across the valley, and it is clear that this layer of old alluvium forms an impervious trough which practically prevents ground water from passing downward to reach the unweathered Koolau rock or the basal ground-water body. A similar section, less completely outlined, was shown by three drill holes (8, 11, 12) on a line across the valley at Reservoir No. 2 (fig. 11). The rock floor of the old valley here reaches as little as 326 feet elevation. From what is known of the gradient and the depth of the valley at School Street, the base of this alluvial fill is thought to pass below sea level in the vicinity of Reservoir No. 5, or the old Electric

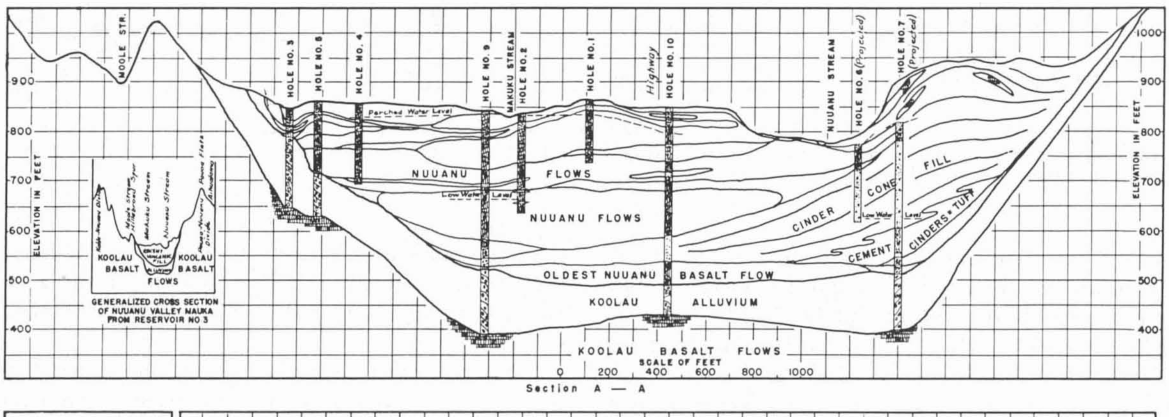

FIGURE 11. Geologic sections of Nuuanu Valley, based on diamond drill holes as indicated in figure 12. In each case the surface of the Koolau rock at the bottom of the deepest valley cutting is overlain by a thick trough-like cover of impervious weathered alluvium, deposited during the period of aggradation when the sea level rose from its deepest recorded position. Late lava flows and cinder beds of the Honolulu series and thinner layers of alluvium make up the total fill of about 400 feet.

Light Station. Farther seaward it serves as the barrier which impedes movement of water between isopiestic Areas 2 and 3 (Beretania and Kalihi).

Three of the deep drill holes, just above the lower old alluvium, pass through the oldest lava flow of the Nuuanu series, at 300 to 350 feet below the surface, the greatest thickness being 50 feet. Above this flow, on the eastern side of the valley, the drill holes show a thick section of cinders and cemented palagonite tuff which forms a part of the lower Luakaha vent cone. In hole No. 7, east of Nuuanu Stream, this cinder and tuff section is more than 250 feet thick and its thinning edge declines to a thickness of 50 feet at 1,000 feet and about 15 feet at 1,700 feet distance. Because of this pyroclastic fill, the axis of the valley at this level was apparently shifted westward and its bottom narrowed in this particular section. Into the valley bottom at this stage was poured a lava flow of the Nuuanu series which appears to be about 1,700 feet wide and which has a known maximum thickness of 125 feet. This lava flow could possibly have come from the lower Luakaha vent, but its position in the valley suggests that it more probably came down the valley from Makuku Cone. Above this basalt are soil and alluvial layers 5 to 20 feet thick which suggest a protracted cessation of volcanic activity. This horizon commonly is about 150 feet below the floor of the valley.

Above this level, as nearly as can be interpreted from the drill cores and drill logs, are several lensy lava flows, of which the lower one, 100 feet thick, probably came from lower Luakaha vent. This is probably the flow which is so prominent all the way down the east side of the valley in the Nuuanu Stream gorge and which appears in the Iwilei artesian wells. Above it lie thinner flows or flow units with an interbedded cinder layer, the whole probably coming from Makuku vent and being the upper flow described by Stearns.

From data now available we cannot in the diamond drill holes positively distinguish between flows which came from the Makuku vent opposite Reservoir No. 4 and those which came from the lower Luakaha vent. Neither can we date the activity of each of these vents in relation to each other. The several lava units exposed in drill holes can be divided into several types in which the chief differences are the presence or absence of zoned augite crystals. At the surface the uppermost flows contain the zoned augites, and the thicker flows exposed just under the surface flows in many places lack the zoned augites. But the diamond drill holes reveal both the zoned-augite-bearing flows and the other kind at various levels, though the zoned-augite-bearing flows appear to be less prevalent in the lower part of the section. Furthermore, the surface exposures on both vent cones indicate that the last basalt issuing from each was of the zoned augite type.

The interbedding of alluvium and other mantle rock formations with the flows in forming the several hundred feet of fill in the valley indicates that the volcanic episodes were spread over a considerable period, perhaps a hundred thousand years. The earliest of the Nuuanu flows probably was erupted in the earlier part of the period of

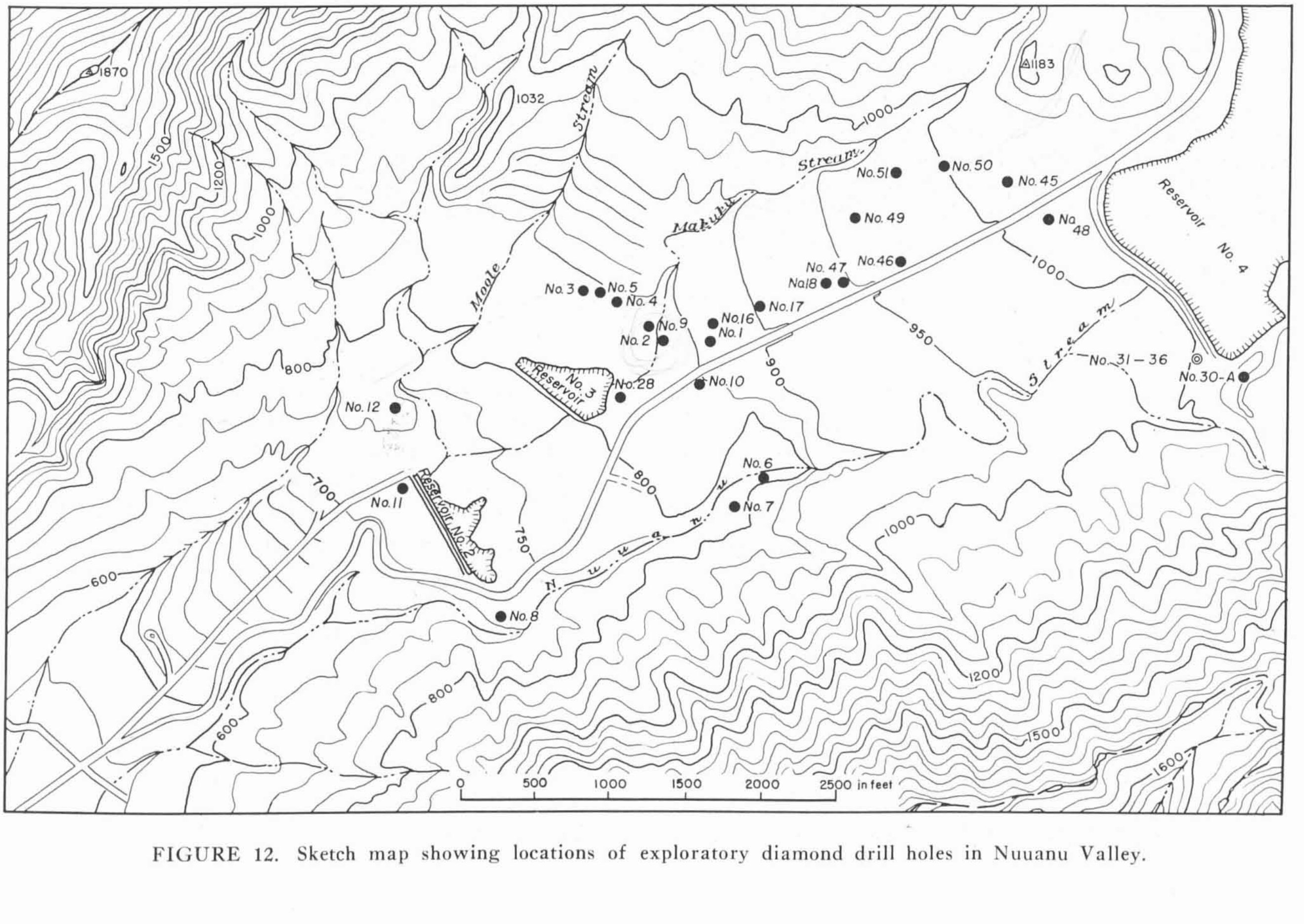

FIGURE 12. Sketch map showing locations of exploratory diamond drill holes in Nuuanu Valley.

general valley filling. This followed the deep erosion of the Koolau Range, which has been correlated with the Kaena and Laie stands of the sea (Stearns and Vaksvik, 1935, p. 68). The later Nuuanu flows may have come much later in Pleistocene time, as indicated both by their relation to the present surface at the vents and by the relationship of slightly older Nuuanu flows to the coral reef formations as shown in the logs of artesian wells. There is nothing about the later Nuuanu flows to show that they are not as recent as the Tantalus basalt and cinders which have been described as Recent, or late Pleistocene; and there is much in the structure of Nuuanu Valley bottom to indicate that its flows of the Honolulu series cannot be wholly allocated to a single earlier division of Pleistocene history.

Makuku vent cone is a rudely circular mass of loosely cemented and much-weathered cinders with an outside base diameter of about 1,400 feet and a high rim point on the southwest side which rises about 150 feet above the outer and downhill base. The rim is only weakly developed on the northern side, and the circular, crater-like form is only clearly seen from points well above it on the west wall of the valley (plate XII). Cinders in this mass range from driblet material 3 to 6 inches across, near the vent, to more uniform, vesicular black cinders in the 4 to 16 millimeter range. Very little of this material is fresh enough to be suitable for thin sections because it occurs in a region of 150-inch annual rainfall. Small patches of cinders of this formation were found at various points within the area of Reservoir No. 4, and east and south of it. Thicknesses of the mantling bed are no more than 3 or 4 feet. There is also a prominent bed of cinders lying under 10 or 15 feet of basalt in the middle portion of the valley flat at various points from Reservoir No. 4 downstream to Reservoir No. 3 and beyond. Tunnel No. 3, in particular, is driven in this cinder formation and derives its water largely therefrom. This cinder bed probably came from Makuku vent. It is presumed that the Makuku cinder formation is identical petrographically with the late Makuku basalt described below.

The lava flow which lies at the surface of middle Nuuanu Valley, between Nuuanu Stream and Makuku Stream from Reservoir No. 4 down the valley to Reservoir No. 2, together with some remnants on the Makuku vent cone itself, is comparatively thin in most places. In drill holes 1, 2, 3, and 10, it has thicknesses ranging from 5 to 35 feet; its average may be no more than 10 or 15 feet. Petrographically this flow is marked by large augite phenocrysts which show conspicuous hourglass extinction due to zonal growth. According to Winchell, this flow contains olivine and augite phenocrysts in a matrix of nepheline, melilite, pyroxene, magnetite, and accessory apatite (Winchell, 1941, p. 73).

Two or three possibly detached arms of the same flow are found in drill holes 4 and 5 near the west edge of the valley bottom. Underneath the known Makuku cinder formation in the middle of the valley is a lava flow about 70 to 100 feet thick which lacks the zoned augites. Since this flow is found in holes 17 and 18 as far inland as the 930-foot surface contour, it is most likely that this flow also came from the Makuku vent. The remainder of the flows shown in the cross section (fig. 11) and revealed by diamond drilling are sufficiently low in relation to the vent cone of lower Luakaha that they could have come from this source, though it is likely that they came at least in part from the Makuku vent. The data from a single line of drill holes are insufficient to determine which vent was the source; it is of course possible that there are other buried vents.

The upper and exposed part of the Luakaha cone forms a slight rounded projection of the lower slope of the eastern valley wall of Nuuanu immediately southeast of the lower Luakaha fall of Nuuanu Stream. Looking across the stream toward it from the west, the mass is seen to show a faintly conical form, and from points above it on the east wall there is still more indication of its identity as a cinder cone. It is about 700 feet in diameter as exposed but is probably much larger at the base. Lower Luakaha fall is a cascade of Nuuanu Stream some 50 or 60 feet high, over the edge of thick Nuuanu lava flows. At its base the Nuuanu Stream flat widens to a circular, flat-bottomed cove, about 500 feet in diameter, which cuts markedly into the flow-mantled valley bottom on the west. Two possible explanations of this alcove are worthy of mention. The cove may have been produced by erosion and undermining of lava flows induced by the encroachment of the Luakaha Cone during some of its later stages of building. On the other hand, the chief mass of the cone may antedate the lava flow filling of the upper 100 feet or more of the valley bottom; and the lava flows may have been molded against the cone, the cinders of which have later been scoured away to form the chief part of the alcove. In view of the depth of cinder and tuff filling and evidently greater age of the cone, the latter explanation is more plausible.

In its upper portion, the Luakaha Cone is composed of medium to coarse cinders and driblet lapilli. There are some trickle masses of basalt in it, as well as some heavy lava flow masses in places. The diamond drill in hole 7 passed through 250 feet of pyroclastic material, the lower 60 feet being well-cemented, mottled palagonite tuff from which cores were readily cut. Below this was 15 feet of weathered talus or alluvial material and then about 15 feet of the earliest Nuuanu basalt, followed by about 110 feet of oldest alluvium, which lies on Koolau rock at about 400 feet above sea level.

A large mass of Nuuanu basalt passes steeply down the northern slope of the cone toward the lip of lower Luakaha fall. It is not clear whether or not this mass came of the same eruption which furnished one of the major flows lying across the valley at 700 to about 775 feet. However, this is quite possibly the case, since it is of similar petrographic character and has the zoned augites in abundance. We can only say that any of the lava flows in the lower valley, either at the surface or deeper, could have come from this vent, equally as from the Makuku or from both in a simultaneous activity, but we lack data to ascribe a given flow specifically to the Luakaha vent. Both the type of basalt with zoned augites and that without are found in lava flows exposed in various parts of the valley floor and in the inner channels of Nuuanu and other streams. In general the type with zonal augites occurs near the top, and that without the augites occurs in thicker flows deeper in the valley cross section. According to Winchell, the earlier type consists of nepheline basalt with a very small amount of melilite. Some specimens show no discernible melilite (Winchell, 1941, p. 71). On the other hand, in certain flows encountered by drill holes at depths of 150 to 200 feet below the floor of the valley (hole 12), there are shown in thin section numerous yellow laths of a mineral identified as melilite. This identification has been confirmed by G. A. Macdonald,[4] but no studies have been made to determine the significance of the yellow color. This characteristic is of considerable value in correlating lava flows from hole to hole in this vicinity.

KALIHI VOLCANICS

This group includes the Kamanaiki lava flow and the flow which came down the east wall of Kalihi Valley, as well as the flow down Kalihi Valley from the west wall near its head and the branch of the latter which went down Manaiki Valley. The Kamanaiki flow and the east Kalihi flow came from the same source on the ridge between the two valleys and near the triangulation point Kamanaiki. No vent structure or cinders were found on the ridge, and the flows were possibly derived from outbreaks in the same dike on the opposite sides of the ridge. The Kamanaiki flow is exposed at various points in the floor of Kamanaiki Valley from 1,150 feet down to 500 feet and appears to have contributed a considerable part of the basalt that lies in the fill of Kalihi Valley and the lower coastal plain.

The east Kalihi branch from the same source forms a small fan on the valley wall, and this flow also made its contribution to the fill in the valley bottom (plate XXIV).

The west Kalihi flow came from a vent marked by a mass of cinders which forms a flat-topped cap to the west boundary ridge near the head of Kalihi Valley and is only 400 feet distant from the crest peak of Puu Kahuauli. A mass of Kalihi basalt about 50 feet thick is found on the eastern slope and shows clearly that this cinder mass surrounds the vent from which the Kalihi flow came. The base of the cinder formation contains fragments of Koolau basalt. The relations have been described by Stearns (Stearns and Vaksvik, 1935, pp. 103–104), and several other masses of more or less weathered cinders or tuff belonging to the Honolulu series are found farther seaward on the west wall of Kalihi Valley. None of them is large enough to be of hydrologic value, nor are they fresh enough to invite detailed petrologic examination.

Puu Kahuauli was also the source of the Manaiki lava flow, whose boulders in the Fort Shafter terrace section in the Damon Road cut indicate that the flow was at least as old as this terrace. This flow has not been found in place in the bottom of Manaiki Valley, and evidence of its presence in the drainage basin is confined to the large black boulders and smaller detritus which are scattered sparingly down the valley in deposits of older gravel and in the modern channel, as well as in the nearby Fort Shafter terrace. Moreover, it cannot be assumed that this flow may lie in a buried valley section, since Manaiki Valley throughout its length is cut down to bedrock and, except at its very mouth, lacks the valley fill common to the larger valleys. The amount of Kahuauli basalt found in the gravel of various ages is not large, but there must have been at least a few acres of the flow on the Manaiki side.

The Kalihi flow from this vent is shown in the north wall of the valley by thickly strewn large black basalt blocks in a triangular area reaching to the axis of the valley. The flow continues down the valley to the point where the east Kalihi flow comes down the east wall. From this point seaward, only very detailed petrographic studies combined with extensive diamond drilling would permit determination of the relative contribution and relationships of the west Kalihi flow, the east Kalihi flow, and the Kamanaiki flow to the lower valley fill.

According to Winchell (1947, p. 15), the basalt from the Kamanaiki vent or vents differs from that of the Kahuauli vent in the absence of dunite nodules, and this basalt, coming both from Kamanaiki Valley and also down the east wall of Kalihi, appears immediately to underlie the coastal flat of the Kalihi-kai district of Honolulu. This flow is considered to be of Waipio age and hence much younger than the Kahuauli flow which, on the basis of the same dunite nodules, is grouped with the Haiku flow and correlated with the Kaena stand of the sea. Both the Kahuauli and Kamanaiki flows are nepheline-melilite basalt, but the former contains more pyroxene and nepheline and less melilite (plate XXV).

Correlation of the Manaiki–west Kalihi basalt from Puu Kahuauli with the Kaena stand of the sea is based on the presence of its boulders in the Fort Shafter terrace, especially in the road cut west of Fort Shafter parade ground. According to Stearns, the Manaiki basalt was found only in the upper part of this section (Stearns and Vaksvik, 1935, pp. 105, 109), but microscopic examination of sections taken by the writer from cobbles and boulders through the whole section shows that this basalt is not so restricted and is found within 5 feet of the contact of gravel on the Koolau rock. There is no indication that these boulders are more numerous near the top of the gravel. It appears that the Puu Kahuauli eruption was at least early in Kaena time and may have been in pre-Kaena time.

Winchell emphasizes the petrographic similarity between the Manaiki–west Kalihi basalt and the Haiku basalt, also correlated with the Kaena stand, as well as the fact of the vents lying on one of the recognized rift lines (1947, fig. 3). Only the former similarity suggests contemporaneity, since the Kamanaiki vent is also on this line and it is believed to be of later age.

The pumiceous, water-laid tuff which occurs in the lower part of Fort Shafter terrace has been attributed

[4] Oral communication, 1946.

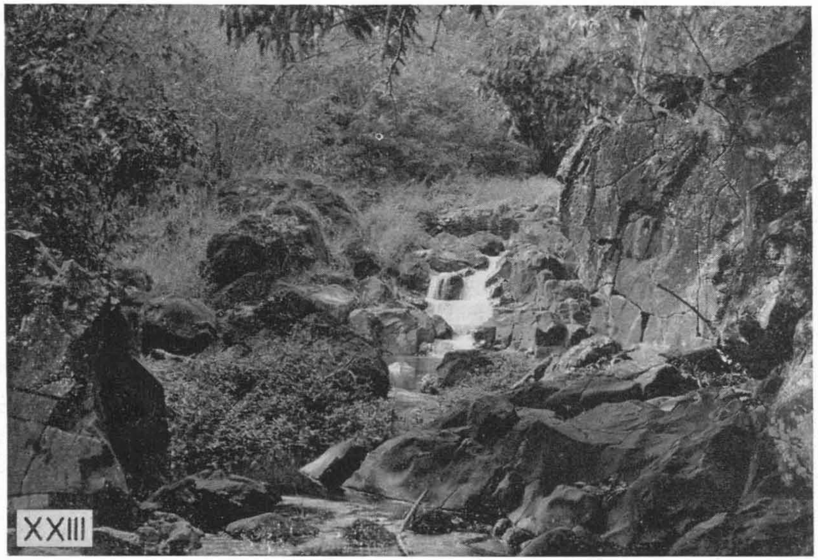

PLATE XXIII. Nuuanu basalt in the channel of Nuuanu Stream. The secondary cooling cracks on the surfaces of the large primary blocks are common features of all the lava flows of the Honolulu series.

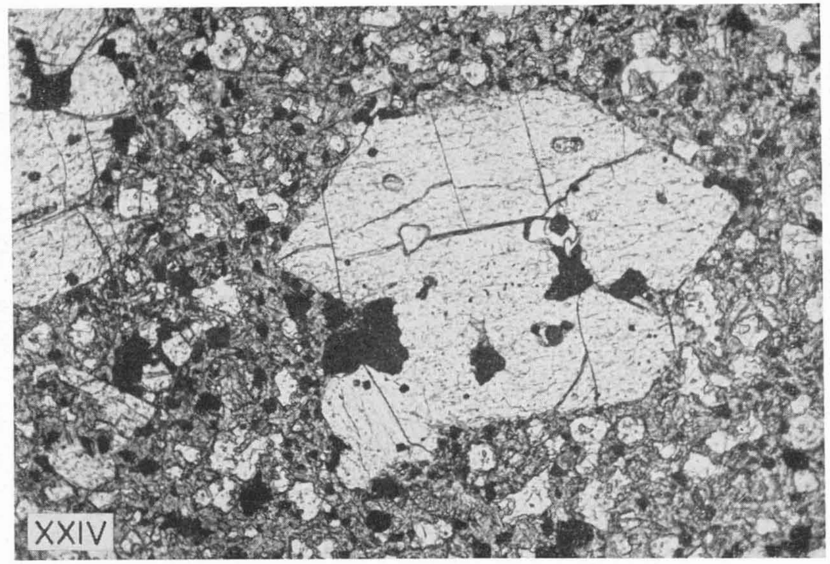

PLATE XXIV. Photomicrograph of Nuuanu basalt from outcrop at Kapena Pool, Nuuanu Stream. The length of the olivine phenocryst is about 0.65 millimeters.

PLATE XXV. Kalihi basalt in Kalihi Stream channel at about 800 feet elevation.

PLATE XXVI. Section on Puuloa Road showing latest Salt Lake tuff (upper and right) unconformably overlapping older tuff (dark at top left), pebbly alluvial beds, and coral reef rock (lowest, light at left). Weathering shows that the interval between the later tuff and the earlier formations may amount to some thousands of years.

to the Puu Kahuauli vent (Stearns and Vaksvik, 1935, p. 104), but this seems to the present writer open to question since the volume of the tuff makes it more likely that it came from the Aliamanu eruption. The distribution of cinders around Kahuauli is so limited and the quantities are so small as to be inconsistent with emplacement of the so-called "fire fountain" tuff of the terrace several miles distant.

SALT LAKE VOLCANICS

Rocks from four vents of the Honolulu series are present west of Kalihi. These are (1) Salt Lake tuff, (2) Aliamanu tuff and basalt, (3) Makalapa tuff, and (4) Manaiki lava flow and cinders from Puu Kahuauli, near the head of the Kalihi-Manaiki divide. The dating of the several eruptions is not easy to determine. There have been at least two periods of eruption, separated by an interval long enough for considerable erosion to have taken place and for a soil to develop and support a growth of trees and other vegetation. The upper tuff layer is the principal mass of gray and drab palagonitic tuff which forms the exposed parts of the Makalapa, Aliamanu, and Salt Lake Craters as well as the rock surface just under the soil over large areas outside the rugged crater masses. The older tuff is in places also a primary tuff, deposited directly from the air; but other parts of it occur as alluvial lenses and finer matrix in the gravel sections of the Fort Shafter terrace. It is not certain that all three of the vents, Salt Lake, Aliamanu, and Makalapa, had two stages of activity; but this is possible, since sections which show the two tuff formations are widespread and occur near and around each of the vents (plate XXVI).

It is clear that the Aliamanu vent was active during the early stage, which Stearns (Stearns and Vaksvik, 1935, pp. 108–111) has included with the Kaena (95-foot) and Laie (70-foot) stands of the sea, and it is his view that all the earlier tuff came from the Aliamanu vent. This is possible, though the exposures on the east and south side of Salt Lake Crater strongly suggest that a crater ring of form similar to the present one was in existence prior to the deposition of the late tuff. There is also a considerable thickness of the earlier tuff at various points near Makalapa vent, though the earlier activity of that vent is not proved. Late tuff carrying fragments of earlier tuff has been found in the Makalapa area, but these do not prove whether the earlier tuff was of Makalapa origin or from the Aliamanu or Salt Lake vent.

The late eruption of Salt Lake is shown by the heavy mantle of tuff around the Salt Lake rim. Stearns concluded that the late tuff came chiefly from Salt Lake and Makalapa vents and states that it can readily be distinguished from the Aliamanu (earlier) tuff by its subaerial character (Stearns and Vaksvik, 1935, p. 127). The present writer recognizes that the late tuff is chiefly primary, aeriform tuff and that much of the earlier tuff consists of alluvial derivatives. However, he believes that some of the layers interbedded in the terrace section are primary and subaerial and that this characteristic is not conclusive in discriminating the two tuffs. In some places the two are separated by a soil layer, but in others there is only a slight break between the primary layers of the two.

Because of the preservation of the shallow Makalapa Crater it appears that here there was an important eruption at the late stage. As to Aliamanu, the problem is whether the tuff, which lies 50 to 100 feet thick on its north rim, is wholly of Salt Lake origin, or partly from Aliamanu vent. Stearns (Stearns and Vaksvik, 1935, p. 109) took the former view, since he says, "The upper tuff can be traced to Salt Lake Crater; hence no doubt exists as to its source."

Granting that this upper tuff can be traced to the mass which mantles the Salt Lake rim and which contains numerous bombs in the Salt Lake area, it is not clear why it cannot also in part have come from a simultaneous eruption of the Aliamanu vent, a possibility which Stearns did not appear to consider. In fact, if this tuff is 100 feet thick on Aliamanu rim, this would suggest partial derivation from the Aliamanu vent, since this upper tuff is nowhere else known to be so thick at equal distances from the Salt Lake vent either to the east or west. According to the writer's observations, the upper tuff at such distances from Salt Lake has thicknesses generally less than 25 to 30 feet, and it is doubtful if erosion has removed more than 5 or 10 feet from many parts of the surface. It is therefore regarded as more probable that the Aliamanu vent was active simultaneously with Salt Lake and Makalapa during the last stage. This activity has been correlated with the Waipio stand of the sea (Stearns and Vaksvik, 1935, p. 127).

In an earlier section the probable age relations of the tuffs of the Honolulu series in this area have been discussed. For practical purposes the tuff will be described as a unit. Within this classification is the upper tuff, mantling much of the surface in the Salt Lake area, and the thin ash mantle found on the northern part of the Fort Shafter terrace, as well as the lower lenses of tuff, including much alluvial tuff, interbedded with the Fort Shafter gravel.

In the mapping it has not been practicable to separate the two tuffs. The lower or earlier tuff is in some places largely alluvial with scattered or more numerous pebbles of weathered Koolau rock included. Even in these sections, however, there are usually some layers which appear to be uniformly mantle-bedded, aeriform ash or tuff representing primary deposition. The chief occurrence of primary earlier tuff is around the shore of Pearl Harbor in road cuts from Aiea southward, in Moanalua Valley, and around Salt Lake. Near Aiea on the main highway, on the Red Hill road south of the South Halawa bridge and inland from Salt Lake, there are outcrops in which the late tuff lies with erosional unconformity on the weathered top of the earlier tuff or on a soil developed from the tuff. In some places the tuff is partly alluvial, but in others, especially along the Pearl Harbor road from Makalapa Crater southward to Puuloa Junction, the early tuff seems to be a primary tuff on which the later tuff lies with very slight break.

Megascopically, the Salt Lake tuff is a fine-grained, compact rock which breaks into irregular chunky blocks.

It has only a moderate tendency to split along the stratigraphic surfaces and often fractures alternately with and across the laminae. The chief structure by which the bedding planes can be identified in a hand specimen is a rude alternation or variation in coarseness of grain due, apparently, to successive pulsations and cessations of deposition of the coarser fragments. Commonly, neither the top nor the bottom of the coarser layers is a sharp contact; the larger fragments, whether of ¼-inch or 1-inch size, are usually partly imbedded in the adjacent finer material both above and below.

The coarser fragments contained in the tuff consist chiefly of Koolau basalt in various stages of weathering and colors with minor amounts of cognate basalt of the same eruption. The finer grains, chiefly below 1 millimeter, are pellets or aggregates of vesicular, palagonitized glass. The whole is indurated by compaction, and in the coarser sizes the grains are conspicuously outlined and most of the interstitial space filled by secondary calcite.

In some layers there are pellets of aggregated ash, or what have been called accretionary lapilli, formed either by smaller nuclei falling through the air and adding fine dust or by rolling down the steeper slopes and similarly adding dust. Also there are fragments of an earlier tuff, not always demonstrably of an earlier eruption and possibly in part from the same eruption. The whole mass has the structure of a gravity breccia, with no discernible imbrication or other orientation of the particles except the rude layering as to size, above mentioned (plate XXVII).

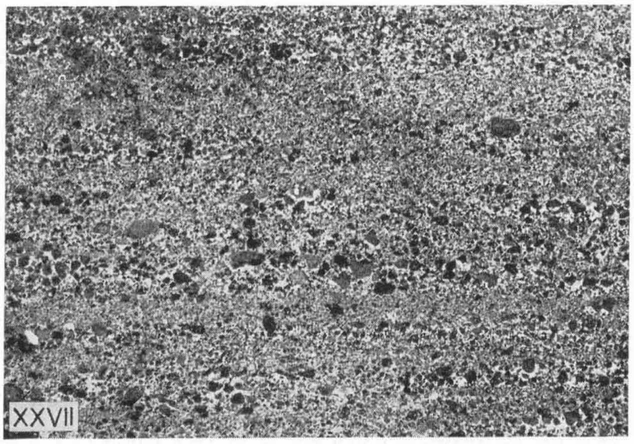

PLATE XXVII. Detail of Salt Lake tuff showing faint banding due to pulsations in settling of different size grades from the air. Discrimination of top from bottom in this mantle bedding is difficult.

Viewed under the binocular microscope at low powers, the particles which compose the Salt Lake tuff show a remarkable variety of colors and textures which appear to have been accentuated by the secondary mineralization and modification which probably took place while the deposit was hot and moist. By comparison with other tuffs of the Honolulu series it appears that the Salt Lake tuffs have much larger proportions of accidental lapilli of Koolau rock and smaller amounts of juvenile, essential glass. Hence, there has been less palagonitization, and the Salt Lake tuff is gray or drab in color, due to the various tones shown by the weathered and altered Koolau fragments combined with the light colors of calcite and other secondary minerals. Under the microscope, nearly every grain shows its own peculiar pattern of growth of secondary minerals and filling of vesicles.

Where exposed to the air, the primary tuff gradually reveals a system of jointing, and the surface often becomes closely checked, the rock breaking into small subspheroidal blocks or crumbs. A few feet below the surface the rock is not visibly altered. This induration produced a sufficiently impervious mass so that subsequent weathering has been less than in the mixed, secondary tuff formation laid down under alluvial conditions. In addition it should be recognized that the primary tuff is mostly much younger and lies in an area of relatively low rainfall.

Petrographic characteristics of the Salt Lake tuffs as seen in thin section have been described elsewhere by the writer (1926, pp. 64–72, 101–112), by Stearns (Stearns and Vaksvik, 1935, pp. 108–111, 127–129), by Macdonald (1940, p. 55), and by Winchell (1947, p. 13). The latter has indicated that he did not find either nepheline or melilite in his specimens of tuff. This is in part due to the fact that so large a part of the tuff of these craters is composed of Koolau detritus and shows so few clear, juvenile pellets to facilitate the identification of essential minerals. As Winchell mentions, the descriptions prepared by Pegau in the writer's 1926 paper include labradorite and perhaps other feldspars. Re-examination of the same thin sections used in 1926 shows these feldspars as present clearly enough but indicates the negligence of the writer and of Pegau in not making clear the fact that these minerals are contained in fragments of Koolau rock which are abundant in the tuff. No clear occurrence of feldspar in the glass of juvenile pellets was noted. On the other hand these pellets, though not abundant in this dominantly accidental, lithic tuff, do contain both melilite and nepheline, so that the tuff of the Salt Lake series is definitely of the nepheline-melilite series.

This fact is further confirmed by the identification of a lava flow of Honolulu basalt between elevations 32 feet and 1 foot above sea level in Artesian Well 160 on the northern inner slope of Aliamanu Crater. This is a melilite-nepheline basalt as reported by G. A. Macdonald (1940, p. 55). It is overlain by Salt Lake tuff and underlain by old alluvium lying on Koolau basalt.

INTERMEDIATE SEDIMENTARY FORMATIONS

INTERMEDIATE ALLUVIUM

The sedimentary accumulations of this region cannot accurately be discriminated on a conventional time scale. A given formation may show a wide range of weathering, but the stage is largely relative to the local conditions rather than to the geologic age. For the purpose of this report the stage of alteration is more important than the geologic age, even if we were able to determine the latter.

The intermediate alluvium is defined as the mass of detrital mantle rock that overlies bedrock, particularly in much of the mountainous area, and which is neither so old or so stable as the older alluvium, nor so recent and so homogeneous as the stratigraphically identifiable recent alluvium of valley bottoms and flat coastal areas.

In the valleys of the many minor side channels in the mountainous section, commonly in the upper portion just below the ridge crest, there is a mantle rock which consists of moist soil and rock detritus which has been moved slightly by gravity from its original position. Because this material at its base may be fairly old and because it is compact, ill-sorted, and not highly pervious, this is included in the intermediate formation (fig. 13).

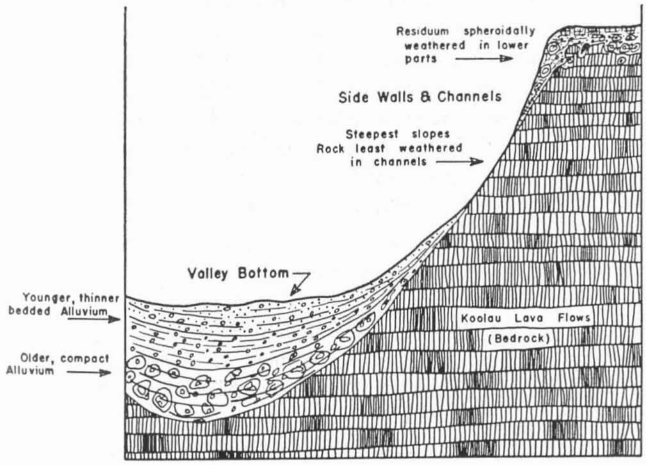

FIGURE 13. Section showing general relation of mantle rock to bed rock, from valley bottom to top of side wall.

Lower down in the side channel is commonly a section where falls and cliffs prevail and where the channel is usually cut on rock and there may be little detrital cover even on the side slopes. Still lower, where the channel has a reduced grade and where it meets the fringe of detrital fans, there is usually an increase in the detrital cover. This is better sorted than above and it often fills the channel so that no bedrock is seen until the main channel is reached. Along the middle sections of the main channels, such as Moanalua or Manaiki, the types of alluvium seen and the pattern of their alternation with bedrock follow a rather systematic pattern. The main channel usually shows a marked meandering from side to side in a belt 200 to 500 feet wide. In the outer bank of each major bend, bedrock is commonly exposed at water level and often continues part or all the way up the valley wall. As the channel swings back away from the valley wall, but continues to bear against the projecting downstream spur, there is often a continuation of bedrock outcrop for a short distance, but this is overlain by weathered gravel, which forms the upper part of the spur. In some places the bedrock is immediately overlain by typical older alluvium, and this in turn by intermediate gravel, the latter with hard, well-rounded, distinct cobbles and a somewhat looser texture. In other places, commonly on the toe of the spur, the intermediate gravel alone is exposed.

From the nature of the exposures, it appears that the older gravel has assumed its character under conditions which have been stable since the period of valley filling which immediately followed the period of great erosion of the Koolau Range. Naturally, the zone which has been continuously one of aggradation or of stability since that time has been that zone from 1,000 feet below sea level to a few hundred feet above sea level. In the inland zone above that, erosion has to some extent continued, since in such areas the effect of a change of sea-level base would not immediately become a factor in erosion.

Hence we do not find, and would not expect to find, the older gravel or alluvium lying on bedrock surfaces at 1,000 or 1,500 feet above present sea level. Here the detrital cover is intermediate alluvium discussed in this section. In a few places this intermediate formation is fairly strongly cemented and moderately compact, but it is still sufficiently distinct from the older alluvium in the one respect that its boulders are mostly hard and protrude from an eroded outcrop and in that it is not so completely expanded and self-rammed by weathering so as to produce a hydrologically tight, self-sealing mass. Locally, this formation ranges from being fairly impervious in its more stabilized, geologically older parts to moderately pervious in the more mobile, steeper parts of the mantle in the mountainous parts. This portion includes the prevailing soil, which might be classified as recent detritus if sufficiently detailed observation were practicable.

In the active stream channels, the loose bouldery and pebbly detritus is classified as recent alluvium. Low level, flood-plain deposits of fine-grained alluvium have also been mapped as recent alluvium, though in many places intermediate and possibly older alluvium may lie underneath.

Such material covers a large part of the inland and mountainous area except for the few areas of stream channels, faces of waterfalls, and cliffs where bare rock in place is exposed. It is believed that old alluvium does not generally occur in the mountainous area under cover of the recent alluvium because of the apparent requirement of deep burial and stability for the production of old alluvium of typical characteristics. Such deep burial and freedom from erosion, movement, or intermingling of new material is dependent on reversal of the land-shaping processes from erosion to deposition, or from degradation to aggradation. The older alluvium appears necessarily to be not only of greater age but also to be found in the valley bottoms and lower parts of valley fans which were affected by the change of base level when the sea level rose and when extensive valley filling took place. Since the inland and higher parts of the various drainage basins continued to be subject to erosion, even though the lower parts of the channels were choked, there was no opportunity for any deposits to be deeply buried or to remain stable for long. Hence it is thought that essentially the entire mass of mantle rock in the mountainous area, with thickness ranging from 0 to 50 feet but probably not over 15 as an average, should be regarded as intermediate alluvium.

This intermediate alluvium is moderately low in permeability but not by any means as impermeable as the old alluvium. In the mountainous areas it is saturated much of the time and not only supports the growth of plants but also is the principal source of shallow ground water which maintains the low flow of streams during all but the most severe and prolonged droughts. The effectiveness of this mantle rock as a retainer of surficial ground water is probably supplemented in an important way by the immediately underlying, somewhat weathered upper zone of the bedrock lava flows. In a few stream channels nearly fresh bedrock is exposed. More commonly the bedrock underneath the mantle rock, in contact with water and with oxygen and carbon dioxide, is weathered to varying degrees. Though parts of the rock retain the structure and exhibit the vesicles and other features of the lava flows, the mass as a whole for some 10 to 100 feet below the surface is sufficiently altered to have a greatly reduced permeability. This is shown even in the stream channels where the interior of the rock is somewhat fresh but where the joints and larger openings show weathering and oxidation which tend to ram the cracks and make them relatively tight to water. If this were not the case and the rock beneath the mantle rock were fresh and hard like quarry rock, the water from rainfall and from streams, as well as from the overlying mantle rock, would disappear quickly into the deeper rock structure.

The coarser fragments, blocks, and slabs which are included in the intermediate alluvium show varying degrees of weathering according to history. Much of such material is sufficiently sound to hold together but is not fresh or hard enough to serve as good concrete aggregate or crusher rock.

Included in the intermediate alluvium is the Fort Shafter terrace formation, named from its type locality at Fort Shafter west of Kalihi Valley (Wentworth, 1926, pp. 64–70). This includes the several beds making up a terrace whose larger or smaller remnants are found adjacent to the range margin, or the higher ground of crater masses from Kalihi westward as far as Waipahu.

The basal portion of the Fort Shafter terrace accumulation in places consists of older alluvium, because the older alluvium, in the coastal area, has only been preserved above sea level in those places where it was capped by terrace beds. There is no standard section, except in the most general terms. Usually the lower part is older alluvium or weathered residuum in contact with bedrock. Above this is commonly a layer that may or may not contain calcareous beds or shells but by its dark color and lamination appears to be of marine deposition. Not uncommonly this layer consists partly of tuffaceous material of subaqueous or subaerial deposition with interbedded pebble layers.

Above the middle layer is a stratum of younger gravel with smaller cobbles than the older alluvium and with cobbles that are harder and less weathered. This layer appears to correspond to the basal layer of what in the lower and middle valley bottoms is called the intermediate alluvium and which here also lies on the eroded surface of older alluvium. This gravel in some places is firmly cemented but in others is much more loose and permeable than the older alluvium. Above this gravel layer in the terrace section is a top layer of soil or in some sections a thin layer of primary tuff from one of the later of the Salt Lake eruptions.

It is quite obvious that any alluvial accumulations that might have been formed in the early period of aggradation would have been left as remnants after a subsequent period of erosion, in just the same places at the ends of spurs and between streams, as would the present day remnants of the later terrace deposits. Hence, it is quite to be expected that existing sections of the Fort Shafter terrace of Kaena age, where they are exposed deeply enough, should reveal the much older alluvium at the base. The dating of the several components of the terrace sections can be only approximate. The most significant time mark in the series is the finishing of the terrace grade in adjustment to the level of the Kaena sea (Stearns and Vaksvik, 1935, p. 109). Because the deposition of the upper gravel was probably fairly rapid and caused by the retardation of streams as they approached grade, this whole upper gravel layer can be assigned to the Kaena stand.

The underlying layer, which is often marine or partly marine and in some places carries oyster beds, appears to represent a time when the sea had reached an elevation equal to or greater than the Kaena stand. If the overlying gravel in the terrace sections was deposited subaerially as its character suggests, this deposition must have taken place after a slight recession of level from that obtaining during the deposition of the preceding marine beds. However, both the marine beds and the overlying gravels, graded to approximately the same sea level, can be assigned to Kaena time. Older alluvium or gravel underlying the marine beds may clearly be very much older, and the thin mantle of ash or tuff is probably of Waipio age and either from the Salt Lake or the Kamanaiki vent.

A most important consequence of the building of the Fort Shafter terrace and the eruptions of the Salt Lake craters was the fixing of the present drainage pattern of streams from Kalihi to Aiea. Moanalua Stream was forced southward to join the lower course of Manaiki Stream, the several branches of Kahauiki were merged on the terrace and now reach the sea through one channel, and the two branches of Halawa were merged in the course of being forced northward by the building of the Salt Lake craters and the forming of the terrace. Thus, the waters of at least seven valleys are now merged in three outlets, Kahauiki, Moanalua, and Halawa, a normal process of integration which has been specially accelerated in this area.

INTERMEDIATE MARINE FORMATIONS

This designation is given to formations deposited since the end of the great erosion period but which are definitely older than the reef formations and beach sands associated with modern and recent beaches and stands of the sea. Very little is known of the detailed stratigraphy and age relationships of these formations, and evidence is available only on relationships of local units which for the most part cannot be traced with confidence. Considerable amounts of both pyroclastic material and terrigenous sediments have been deposited under marine, offshore conditions in the upper part of what is now the caprock, but they are known imperfectly and almost wholly from drill logs. Gravel and clay layers that are in unoxidized condition and of gray color are thought in part to be of submarine deposition; lacking fossils and lacking outcrops showing structural relationships, discrimination is not precise.

Calcareous formations standing more than 30 feet above sea level in the Honolulu area are chiefly of eolian origin. Reef limestone masses at 25 to 30 feet above sea level are found east and west of Diamond Head, west of Manoa Stream and seaward from Rocky Hill, at various points from Honolulu Harbor west through Iwilei to Kapalama Stream, and also in a broad area against the Honolulu basalt fan in Kalihi-kai. The reef remnants widen on the margin of the Puuloa peninsula and form a more continuous surface of over 20 square miles west of Pearl Harbor in the Ewa Coral Plain. Certain lithified dune formations in the Diamond Head and other areas of Oahu are apparently older than the Waimanalo stage, but evidence is lacking for assignment of any of the reef formations of the southern coast from Wailupe to Barbers Point to a stage older than the 25-foot Waimanalo stand. These reef masses have formed a platform on which pyroclastic materials and land-derived sediments have lodged and have resisted erosion at various stages to fix the outlets of several of the major streams. Reef limestone of this age served as a platform on which the Sugarloaf lava flow pooled in forming the thick mass of Honolulu basalt now nearly worked out in the Moiliili Quarry. This limestone is also one of the four chief formations encountered in pipe and sewer trenches in various lowland sections of Honolulu.

RECENT SEDIMENTARY FORMATIONS

RESIDUAL FORMATIONS

Perhaps the second most important formation in the Honolulu area from the hydrologic standpoint is the residuum which develops from weathering of the Koolau basalt or any other basaltic formation exposed above sea level. This relatively impervious blanket exerts great influence on the infiltration of rain water, determining where and in what proportions it enters the subjacent aquifer, and it also acts indirectly through control of vegetation. The caprock itself, though it is not classed as a residual formation because its components are the broken and somewhat weathered debris of rocks transported from elsewhere, also owes its character in very large measure to weathering in place. Because it was accumulated successively from the bottom up and because various parts had an opportunity to become rather completely weathered while they lay at the surface, the caprock could be called a compound or progressive residual formation. However, the purpose of this section is to describe the true residual material developed directly from the Koolau basalt.

Chief areas of residual materials are the surfaces of flow-slope facets. Excepting the thick alluvial fills in the larger valleys, consisting in part of weathered older alluvium, the residual materials of flow-slope facets are probably the most effective formations for excluding rain water from infiltrating into the Koolau aquifer and reaching the basal water body. In view of the increasing settlement of the flow-slope facets, this is a very desirable condition, since such a settled area should not be an intake area for the water supply. However, an unfortunate and ill-planned condition is the lack of sewers in several of these upland areas and the mandatory use of cesspools, which by law are required to be so constructed that they drain downward effectively. In these areas, such drainage is drainage downward into the permeable, unweathered Koolau rock which underlies the weathered residuum and thence more or less rapidly down to the basal water itself. Clearly this is an objectionable state of affairs from the standpoint of ultimate sanitation, however desirable may be the use of functional cesspools for immediate sanitation.

Long exposure of lava flows to the rain and the atmosphere results in progressive decomposition which proceeds downward from the surface and inward from the cracks left initially in the cooling lava flows. Several distinct zones may be recognized, though the soil profile is complicated by the deep physical disruption in extrusive rocks.

At the top is usually a layer of bright or dark red, fully pulverized lateritic soil. This layer has lost all structural evidence of its derivation from lava flows and shows no vesicles, or jointing, or other structure that has survived from the lava flows. Instead, this layer, if it has any structure at all, often has a lumpy or irregular columnar structure due to drying after being wet, or it may display small slip surfaces due to its being heaved and rearranged under alternate wetting and drying.

In some places where the soil has been hot and dry for a long time the process of chemical change has proceeded farther, and thin caps of a material still more highly ferruginous than the soil have been produced. This material is a low grade hematite and may contain as much as 50 per cent of metallic iron, whereas the residual soil generally runs from 20 to 30 per cent iron oxides and not over about 15 to 20 per cent metallic iron. Such deposits, however, are very limited in extent.

The layer of red, structureless residuum is from a few inches to as much as 20 or 30 feet thick. Where such completely weathered material is thicker, in some instances a hundred or more feet, it usually displays some distinction between the several lava flows from which it came and in deeper parts displays vesicles and other structural relics of the flows. The layer of red residuum may contain occasional kernels of sound, very little-weathered basalt surrounded by progressively weathered shells in spheroidal configuration.

The next layer downward is one in which the kernels dominate, with the surrounding shells making a continuous structure. Such structure with conspicuously large kernels is more characteristic of the weathering of thick flows, especially aa flows. The most weathered material, along the lines of the interkernel cracks, is commonly soft, red earthy material comparable to the surface layer. From these cracks, radially inward toward the core and across the several shells, the color changes progressively from red to fainter pinks, grays, gray-purples, and yellows, with much individual variety. The shells are sufficiently strong not to crush between the fingers but can easily be carved with a knife, and larger slabs are easily broken with the hands. Toward the core the shell slabs may become gray, moderately sound rock.

In some sorts of lava flows, the cores shell off so as to expose hard, dense, black or dark gray rock with very little weathering. In others, the kernels are somewhat more weathered on the outside and may be weathered to the center. The exact relation between the composition of the rock, its physical constitution, and the immediate local condition of moisture and weathering which causes very great variety in the course of chemical and physical weathering from flow to flow and place to place, is not known and would probably prove to be very difficult to define.

PLATE XXVIII. Spheroidal weathering in basaltic residuum. Weathering and volume increase commence along the major cooling cracks in the rock mass and work inward, developing the spheroidal kernels.

PLATE XXIX. Residual kernel of Koolau basalt, isolated through removal of the surrounding weathered soil and subsoil by rain and wind scour.

In many places, probably mostly in pahoehoe flows, the lava flows do not weather to develop cores or a notable spheroidal structure but instead seem to become softened throughout to a chalky constitution which tends on close exposure to the air to break up into small blocks about 1 inch or less in diameter (plate XXVIII). In certain situations on the eroding edges of ridges, the bare surface shows the weathered rock intimately divided into such blocks which are gray inside and red or pink along the joints which bound them. The detritus which ravels from such a surface is wholly composed of these chunky, subspheroidally rounded crumbs of weathered rock. Or, the shell parts of a spheroidally weathered terrane may ravel in this way, leaving occasional spheroidal cores perched as residuals above the general surface (plate XXIX).

The important factors in the formation of a residual cover are the weathering and chemical modification and the thick accumulation of the modified material. In situations where the weathered and expanded material falls or is eroded away as soon as it is formed, no residual formation is produced. In places where the residual material is no more than 5 or 10 feet thick and is loose and free to heave, the blanket may not develop any great imperviousness. But on fairly large areas of land of not too great a slope, such as the surfaces of some of the flow-slope facets where the residual material lies 25 to 100 or more feet thick, the larger part of it is under sufficient load so that the expansion which accompanies continued weathering produces high pressures. These pressures ram and tighten the material without greatly displacing it and thus produce a very effective seal or barrier to the movement of water.

The most readily observed areas of Koolau residuum are those on the several flow-slope facets. These areas which approximate the original surface of the flows are often underlain by 20, 30, or more feet of deep, red, soil-like residuum which only toward the bottom gives way to gray, mottled fragments of shells and a large proportion of kernels. On much of the lower margin of the flow-slope facets, and often in somewhat eroded areas, the lower parts of the residuum, or bare rock, lie at the surface. Locally, in such areas, there may be more effective infiltration to basal water, but over most of the facet area where the topography is smooth the blanket is probably highly effective and prevents any but a very small share of the rain water from passing through to basal water. It is difficult to determine categorically the limits to be observed in mapping the residuum, and the writer has had to rely on general impression in indicating those areas which seem large enough and are mantled with thick enough residuum to operate effectively as water-diverting blankets.

Inland from the apex of each flow-slope facet, the crest of the narrow ridge with occasional wider places at the peaks, is the site of the chief residual materials; but there are only scattered opportunities for observations on the exact condition. Because of the small areas and greater ease of removal down adjacent slopes, there are here only small amounts of structureless residuum, and because of the higher rainfall and greater amount of plant growth, this upper layer is more commonly gray, drab, or black. In the later stages of weathering, the extreme end-product at these higher elevations and in damper situations may be a high-alumina–high-silica residue, showing removal of iron rather than its retention and concentration. The formation of ceramic clay under these conditions has been discussed elsewhere (Wentworth, Wells, and Allen, 1940).

Beneath the more completely weathered soil layer which is commonly present under the rounded tops of knobs and more commonly absent from the crests of the saddle parts of ridges, is a zone of weathered rock comparable to that below the structureless material in the facet areas. This is the fairly soft rock in place, exhibiting the characteristic structures of the lava flows, which is commonly seen in fresh-cut mountain trails. In the mountainous sections, where primitive trails mostly followed the actual crest of the narrow ridge, the later, so-called "sidewalk" trails have been cut by C.C.C. workers on a more uniform grade around the sides of the knobs and often at about the level of the lower saddles. Much of the total length was cut in soft-weathered bedrock in place, having slope angles of 45 to 65 degrees, and giving a clean-cut vertical exposure of the bedrock of 3 to 6 feet or more.

The nature of the weathered rock is indicated by the fact that the trails were dug without use of explosives or power tools and that, a decade after cutting, the tool marks are still visible in many places. Only rarely have hard rock cores more than a foot in diameter been encountered. In most places the digging has not only been by pick and shovel but both the sides and tread of the trail have been neatly shaved to the desired shape. Locally, slides have destroyed short sections of the trails, but for the most part, since the trails were cut chiefly in the rock structure, no sliding has occurred. Had trails been cut in slopes underlain by intermediate alluvium, more normally subject to sliding, there would have been a larger proportion of destruction.

On leaving the crests of these ridges and traversing down the lateral gullies, where outcrops are more abundant, it is most common to pass 100 feet or more down the slope before rock is seen in place and often 200 feet or more before rock sound enough for thin sections is seen. Since there is some weathering from the sides, this does not mean that the sound rock lies 200 feet vertically under the crest of the ridge. It is more likely that the weathered rock forms a sort of perched cap, thicker at the top but overlapping down the sides to a point where erosion keeps pace with weathering in the channels (fig. 13). This weathered rock presents a complete range from slightly weathered Koolau rock, through deeply weathered rock, to structureless residuum. Hydrologically, much of the weathered Koolau rock should be considered as belonging to the residual formation, despite the possibility that petrographers might draw the line in some intermediate position.

The narrowness of the ridge cap of residuum, both in its effect on erosional removal and also in preventing the development of high pressures, probably determines that these particular occurrences of residuum do not become so tightly rammed and are not as a whole so impervious as the larger facet blankets. On the other hand, since they are of smaller size they may almost as effectively divert rain water off the few flatter areas and down the steeper channels whence the more torrential rainfall passes down to valley-bottom areas of caprock. Qualitatively, the ridge-top residuum and the intermediate alluvium or taluvium of most of the steeper slopes, conspire to pass a great share of the rain water more rapidly off the slopes than would be the case with bare, unweathered rock. But, on the other hand, both of these formations retain much water and regulate stream flow for long periods after rains.

The field measurement of permeability in masses of some tens or hundreds of feet in extent has not been practicable; even if it were, its interpretation in terms of actual infiltration would be difficult. Hence, it is impossible to make definitive numerical statements concerning the individual formations, however clear the relative hydrologic qualities may appear.

EOLIAN, TALUVIAL, AND COLLUVIAL FORMATIONS

Small areas of eolian silt and eolian lag crumbs up to 2- or 3-millimeter sizes can be seen on nearly all the upper flow-slope facets at eroded edges. The eolian formation is rarely over 1 to 2 feet thick and lies on the residual soil. Limited extent and thickness, as well as position on the top of thick residuum, mean that the eolian materials, while of systematic interest to the student, are of negligible hydrologic importance. These deposits are mostly adjacent to active erosion scars which may now be somewhat more numerous than they formerly were and which are supposed by many to have been started by grazing, trail cutting, or some other modern human activity. This is true in part, but the writer believes that breaks in the soil cover through slides and deflation from exposed points are normal processes in a rugged country and have always been operative (Wentworth, 1943, p. 63) (plate XXX).

As stated under the heading of intermediate alluvium, much of the steeper-sloped, higher topography of the Koolau Range is veneered by a comparatively thin mantle of detrital material or mantle rock. This is distinguished from underlying bedrock, or from weathered residuum which is essentially in place, by the fact that it has to some extent been moved and shows some evidence of sorting or of mixing of fragments from different outcrops. The upper part of this material is modern, of contemporary placement through the agency of gravity alone or of gravity aided by water; hence, it may be regarded in part as one of the recent sedimentary formations. Taken as a whole, the modern mantle rock is of rather complex origin. Frequent soil avalanches, whose traces are often seen after rainy periods, show that a perfectly normal, usual mode of movement for soils and rock debris in the steeper areas, is by slipping along a surface usually only a few feet, 1 to 4, beneath the vegetation-covered slope (Wentworth, 1943, pp. 53–64). Vegetation, roots, etc.,

PLATE XXX. Scar of large soil avalanche on the west side of Lulumahu Valley opposite the West Waihi saddle. This slide probably took place in late August, 1939, having been first recorded on September 6.

are carried with the soil which commences movement as a mass but breaks up as it slides. The surface underneath is left bare of vegetation and usually shows the edges of harder layers of bedrock. These may be faintly striated in the lower part of the scar and indicate that the collapse has been due merely to slippage of the soil veneer from the rock beneath. The slopes on which such slips take place range, generally, from 45 to about 55 degrees. Near the top these slips often end in a nearly vertical bank where the surface of movement curves upward; but throughout their length these soil avalanches are definitely different from slides due to structural collapse along curved surfaces, as discussed by Becker (1916) and others.

After a slip has taken place, plants immediately begin to invade the bared area where there is still soil in crevices and zones of weathered rock. After 2 or 3 years, there is likely to be a rather complete cover of annuals but a marked absence of shrubs and larger trees. It appears that it may take one or two decades at the least to develop a strong cover over such a slide. Soil avalanches often bring up sharply in the channel of a main stream, occasionally with a slight lapping up on the opposite slope. The result is a disordered pile or fan of mud, stones, trunks of trees, and other plant debris subject to selective removal by waters of the main stream; but a part may remain for several years.

Occasionally, individual blocks, ranging up to several tons in weight, may break loose, undermined by the weathering and water-soaking of material below, and crash downslope for several hundreds of feet. A notable instance was in Waiomao Valley, where a mass of Kaau basalt from a previously unknown outcrop, and weighing probably about 25 tons, crashed down the west slope to the channel of Waiomao Stream. In its course it broke the 6-inch pipe line from Palolo Tunnel and overturned and broke off many trees, some as much as a foot in diameter. Some were broken at a height of 15 feet above the ground. These facts are stated to indicate the variety of gravity and colluvial processes by which the mantle rock is moved and accumulated in the mountainous areas. In a few places a ledge of rock may be so exposed and wasted by physical weathering that a talus slope of loose angular blocks is formed below it, like the screes of certain continental areas; but these are mostly found in drier areas such as some parts of the Waianae Range or at high elevations on Mauna Kea or Haleakala and are not common in the Honolulu watershed area.

RECENT ALLUVIUM

The term alluvium as used in this report includes all water-laid terrestrial sediments except certain parts of the inland mantle rock which are considered under the preceding heading. Both coarse and fine sediments are included. In the channels of modern streams small amounts of well-sorted gravel consisting of rounded pebbles and cobbles are found. Similarly, in banks adjacent to such channels a few layers of such gravel, having high permeability, are found interstratified with finer, less well-sorted and less permeable sediments. In general, however, clean gravel consisting of hard, fresh, and well-rounded fragments is very rare and limited in amount. In a few places a landowner might be able to screen and wash out, with considerable effort and selection, 1 or 2 yards of gravel, which, as coarse aggregate, would serve in producing an inferior grade of concrete. It is doubtful if any such gravel selected from any inland situation would pass the most lenient of rattler tests of engineering practice. There are a few places on the Oahu coast where harder, cleaner gravel can be had in very small amounts, but these are of negligible commercial importance. In the mountainous area such gravel as is found in stream channels contains a large percentage of fairly well-rounded pebbles, but most of these are weathered to the hardness and mechanical durability of tuff or of a soft brick. Some can be readily carved with a knife. They grade to a few pebbles of moderately sound basalt, but the deposit as a whole, even when washed clean of finer stuff, is well on its way to complete chemical weathering and if laid in a thick deposit would show only a moderate and rapidly diminishing permeability. Rapidity of chemical weathering in this climate is such that capacity of the rock to hold up in discrete particles and remain permeable as a detrital deposit is destroyed by weathering, both en route and in the deposit, before the lower layers are sufficiently covered to protect them from further weathering.

Partly because of the dominance of chemical weathering, partly because of the fineness of grain of the parent rocks, and partly because of the steep slopes, short streams, and imperfect sorting, the erosion of Hawaiian land areas results in sediments that, predominantly, are of fine grain and are ill-sorted. Much of the modern alluvium is difficult to describe in other grade terms. Much of it is of the grain size of clay but is not chemically a clay because of the presence of too much iron and coarser detritus. Some of it is predominantly of silt grades but is not well enough sorted to merit this term. Loam is perhaps no more applicable than the other terms and, except in very limited rill channels or with imperfect sorting and shaping, fluviatile sand is nonexistent (Wentworth, 1937, pp. 97–103; 1939a, p. 20).

The fine alluvium forms an extensive cover over flood-plain areas and over reef and shore flats, varying in thickness from 1 to commonly not over 5 or 10 feet. Lenses of coarser gravel or rubble occur in it, and also various other materials such as plant debris, animal remains, etc., accidentally incorporated with it. Its colors range from dark brown or almost black when wet, to lighter browns and grays when dry. On facet areas where it contains more residual material, the colors grade to red, but red is not common in the flood-plain areas. Material washed onto reef or shore flats may have any color appropriate to the source area (Chapman, 1946, pp. 985–995).

A variety of dark muck which develops characteristically on marshy flood-plain areas and in small artificial patches terraced by stone retaining walls of early native origin, is known as "taro-patch clay." According to Stearns (Stearns and Vaksvik, 1935, p. 171) this is "probably a slightly reworked sediment of the Waimanalo stand of the sea." While the present writer agrees there may be incorporated in this type of clay some derivatives from the Waimanalo stand, he is doubtful if the occurrence is limited to positions within 25 feet of present sea level, since many valley deposits at from 100 to 300 or more feet above sea level appear to be comparable to it. He believes, rather, that the black clay is formed in any places which are protected from erosion and deposition and where incorporation of carbonaceous plant debris and reducing conditions are dominant.

RECENT MARINE FORMATIONS

Offshore from the Honolulu coastal plain there is a living coral reef on which there is moderate, if not vigorous, growth of reef-forming and reef-dwelling organisms. This has been described by Pollock (1928, pp. 1–56) and by Edmondson (1928, pp. 1–64). In places a reef platform extends inland to the beach and may pass under it. Parts of the reef and reef platform, which may be classified as recent, lie in some places on older reef and detrital limestone which extend down to depths of over 200 feet below sea level (Artesian Well 23) and in other places overlie post-Koolau basalt flows, gravel, or other terrigenous formations. The thickness of limestone revealed in Well 23, though no very far-reaching conclusions can be based on one section, probably imperfectly recorded, suggests that the area in the lee of the old cone of Diamond Head may have been for a long time a favorable place for coral growth. No means is yet at hand for distinguishing recent from earlier Pleistocene reef formations, though a sufficiently critical study of the proportions and structure of various organisms in adequate borings or outcrops might develop such a basis.

The principal significance of the modern reef and reef platform is in the function of providing a continuous supply of shell and coral detritus for the beach maintenance, in the controlling effect on wave action on the beach, and in the providing of a stable shore flat on which beach deposits, terrigenous debris, and artifical fill have been and are being placed. This function in promoting the building and preservation of a coastal plain has been active during much of Pleistocene time and has been the major factor in the development of the rather complex coastal plain of both windward and leeward Oahu.

Beach formations of sand and gravel are the most conspicuous detrital marine deposits, though quiet-water, lagoon deposits of calcareous silts, etc., are also present and were intermingled with terrigenous accumulations in the flat areas inland from the beach ridges. In earlier geologic time, especially east of Diamond Head, there were extensive wind-drifted accumulations of finer beach sand to form dunes, but there appears to have been very little action of this kind in modern times west of Diamond Head.

Extensive artificial filling has taken place along the shore flats of both the Honolulu and Pearl Harbor areas. Part has been in connection with dredging operations and airport construction and the rest in the form of road building or top-soil fillings of lawns and gardens. The entire area on which artificial filling has taken place is part of the caprock; there is no primary effect on the artesian water.

DRILL HOLES AND EXCAVATIONS

ARTESIAN WELLS

The first artesian well in Hawaii was drilled at Honouliuli, on the west side of Pearl Harbor, in 1879. A second successful well was drilled on the present Wilder Avenue, west of Metcalf Street, in 1880. Following these pioneer wells, a great many others were drilled between Diamond Head and Barbers Point, and these, by practical test, outlined the area within which the artesian condition exists. In the Honolulu area, through various records in newspapers and elsewhere, the history of this drilling is rather well known, as shown in table 6.

TABLE 6

DATES OF DRILLING OF ARTESIAN WELLS, HONOLULU AREA

YEARS	NUMBER DRILLED	PRESENT STATUS		
		Sealed	Recased	Remaining
1879–1890	67	44	8	15
1891–1900	37	12	6	19
1901–1910	21	6	3	12
1911–1920	19	3	1	15
1921–1930	23			23
1931–1940	6			6
1941–1946	4			4
Total	177	65	18	94

This table shows that the most active drilling came in the first decade, followed by decline to a nearly steady rate of two per year through the period 1901–1930. Unfortunately, during the period of most active drilling there was no supervision or public agency either to collect or to interpret well logs, and very few carefully kept logs are available. Owing in part to the fact that valley-fill formations in Hawaii are barriers and not aquifers and that the water is found in the bedrock of the ridges and spurs, understanding of the artesian mechanism was developed only very slowly, by a few persons, commencing in the first decade of this century.

Drilling in the Pearl Harbor area followed a time pattern similar to that in Honolulu, but the records are less complete (Stearns and Vaksvik, 1938).

It might appear, from table 7, that the drilling in the Pearl Harbor area was somewhat retarded behind that of the Honolulu area, with the maximum coming one decade later. This is only partly correct, however, because of some 84 wells showing the first record of head or salinity in the second or third decade (1891 to 1910), the majority were probably drilled prior to 1890. The available records show general surveys of heads and salinities as taking place in 1902, 1908, and 1910, with only very scattered notes on conditions at any earlier date (Stearns and Vaksvik, 1938).

Total number of bore holes put down for water in the Honolulu and Pearl Harbor areas is upward of 450. It should be noted that in the numbering system now in use, there are many groups of wells, connected by headers into one pumping station, in which from 3 to as many as 20 wells are given letters under one number. Of these wells, despite the incompleteness of early records, certainly 250, and quite likely nearly 300, were drilled before the end of 1900. Only about 40 have been drilled since 1930.

On the other hand, about 80 wells have been sealed during the last two decades, and at least half of the remainder are inactive and will be sealed in due course.

TABLE 7

ARTESIAN WELLS IN THE PEARL HARBOR AREA*

DATE OF DRILLING			WELLS OF COLUMNS 2 AND 3		WELLS OF ANY DATE	
1	2	3	4	5	6	7
Period	Recorded	Inferred*	Sealed	Recased	Sealed in this period	Recased in this period
1879–1890	10	2	2	1		
1891–1900	94	39	8			
1901–1910	23	45	13	5		
1911–1920	4		1			1
1921–1930	26	14	2		2	
1931–1940	21				13	5
1941–1946	11		1		12	
Total	289		27	6	27	6

*This table has been prepared from all available sources chiefly to give a general picture of the rise and initial fall of artesian wells as water sources. It is unlikely that the data for earlier wells are free from error. Column 3 carries wells whose first record of salinity, head, or discharge is found in the decade shown. Undoubtedly many of the wells of the periods 1891–1910 were drilled in preceding decades.

In the Honolulu area, which may be regarded as farther along in the process of retirement of artesian wells, there are 32 wells that still produce about a half mgd each, and, of these, 25 are those supplying the city's three pumping stations. About 22 more produce over 0.1 mgd each. These 54 wells represent what may be called the active remainder of the total of 177 wells originally drilled. It is quite possible that by the year 1980 not more than a half dozen wells producing over 0.5 mgd each will survive in the Honolulu area.

The numbers by which individual wells are designated in this report are those of the revised numbering system set up by Stearns and Vaksvik (1935, pp. 463–467) which starts at the east point of Oahu and proceeds in a clockwise direction around the island. (See reference cited above for conversion table between the old and new series.)

The logs of these wells were compiled by Palmer (1927), and later by Stearns (Stearns and Vaksvik, 1935), and yield some general information about the structure of the cap rock (see fig. 14). The most readily identifiable rock is the coral reef rock. It is striking that wells from 9 to 28, west of Diamond Head but east of Manoa Stream, show a predominance of coral reef and related rocks from depths as great as 800 feet below sea level, with the most continuous stratum at —260 to —120 feet. Eastward, the wells near the Kaimuki pump station show little coral and pass from weathered terrigenous material or weathered late flows into Koolau bedrock at less than 100 feet below sea level. This rock is probably the extension of the St. Louis Heights spur. Wells 37 to 41 are similar and at about —100 feet pass into the Koolau rock of an extension of the Round Top spur.

Westward, commencing with Well 51, more coral appears, forming a conspicuous mass from —200 feet to about —60 feet and extending with this thickness as far west as Queen's Hospital. There are scattered masses of coral at greater depths. This coral mass is overlain by the Punchbowl tuff and must have grown on a thick mass of weathered sediments lying on the Koolau rock. West of here only small amounts of coral are encountered until we reach Wells 162 to 170 in the Puuloa area where the coral reef is nearly continuous from —240 feet to the present surface at a few feet above sea level. Scattered coral strata are found below this depth, down to

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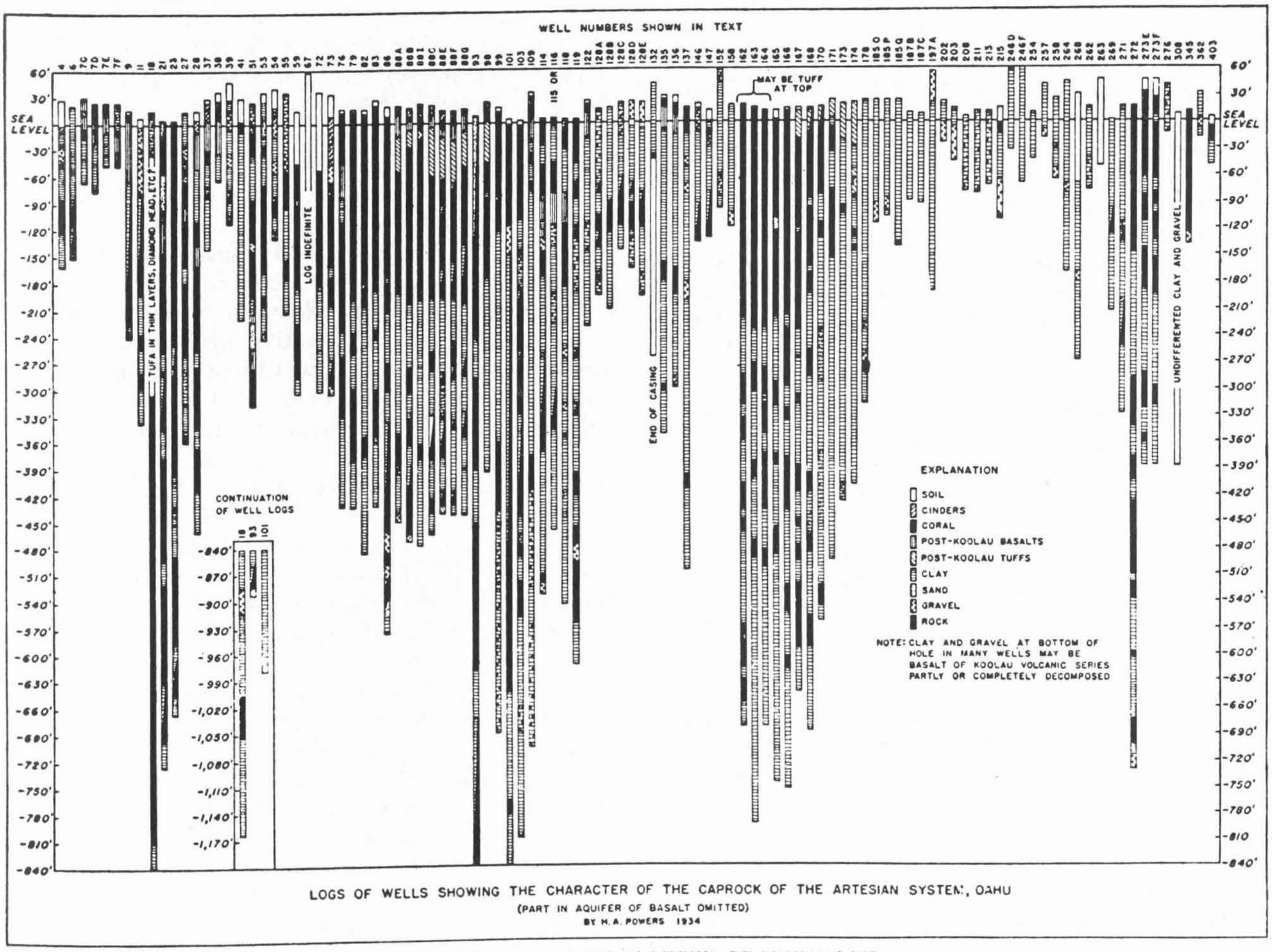

WELL LOGS OF OAHU PLOTTED GRAPHICALLY

NOTE THE ALTERNATION OF REEF WITH NONCALCAREOUS SEDIMENTS, INDICATING ALTERNATE PERIODS OF EMERGENCE AND SUBMERGENCE, AND ALSO THE NEARLY CONTINUOUS REEF ABOVE THE *300*-FOOT LEVEL

FIGURE 14. Composite plot of artesian well logs (compiled by H. A. Powers). (After Stearns and Vaksvik, 1935.)

more than 600 feet below sea level; but it appears that coral growth did not make a widespread start at so early a stage. A very similar condition is shown in Wells 272 and 273 on the western side of the Pearl Harbor entrance. On the other hand, as might be expected from the geographic situation, the wells located around the inner margin of Pearl Harbor, numbers 178 to 263 on the chart, are drilled chiefly in clay and gravel to depths of 50 to 200 feet before reaching Koolau rock.

The stratigraphic logs of these wells, in addition to their hydrologic behavior, show that in the Pearl Harbor and Honolulu areas the surface of the Koolau rock is covered continuously from some elevation above sea level to over 800 feet below sea level, and probably in most places to much greater depths, by a thick sedimentary wedge. Gravel and other weathered alluvium beds are predominant in this mass, with subordinate amounts of coral reef and post-Koolau tuff, cinders, and basalt. Weathering of the whole has produced a highly impermeable formation, and there is no evidence of continuous or extensive layers or lenses having greater permeability.

It is evident from a great many well logs that the Koolau bedrock is much weathered, in places to 50 or 100 feet below its surface, under the cap of weathered sediments. The same weathering of the upper parts is shown around the margin of Pearl Harbor near present sea level. While it is usually possible to discriminate between the weathered sediments and the underlying, weathered surface of bedrock in adequate outcrops, it is not possible, even with good samples, to make this discrimination in a deep drill hole, much less with the driller's report of clay or gravel. Hydrologic character is gradational, and the caprock, while consisting chiefly of sediments or secondary volcanic material, also includes functionally that part of the subjacent Koolau rock which has the nature of a water barrier as distinguished from an aquifer. Further, the logs of drilled wells show us that the entire thickness of the caprock should be regarded as a potential water barrier. While it is true that the artesian condition is first revealed when the drilling passes through the bottom part of the caprock or of the weathered surface of the Koolau rock, it is in fact the whole thickness of the sedimentary mass that serves as a caprock, rather than any specific bottom layer next to the Koolau formation as some have thought.

OBSERVATION WELLS

The drilling by the Board of Water Supply in 1945 and 1946 of four 12-inch holes exclusively for observation purposes represents a notable advance in practice. These are located in the Manaiki, Waimalu, Waiawa, and Kunia sectors of the Pearl Harbor area and are of 12-inch diameter to permit use of a large float. The wells are drilled at such points as to be in Koolau rock at sea level and thus indicate non-artesian, free water-table levels. Each well is surmounted by a pre-cast, concrete housing for a clock-driven recorder. In the past, most water-level records have been taken from wells originally drilled for water production and in many cases from wells either subject to part-time draft, or at least so closely related to such draft that they have not yielded records of the undisturbed water level. The present observation wells, after a period of several years overlap, may eventually replace the series now used as index wells for the Pearl Harbor area.

DIAMOND DRILL HOLES

A total of 84 diamond drill holes has been drilled by the Board of Water Supply in the Honolulu area. Data on these holes are tabulated in table 8.

The holes enumerated in table 8 represent an aggregate of about 18,000 feet of drilling. In general, the drilling has had a threefold objective: first, the recording of the rock structure by means of notes and preserved cores; second, the determination of ground-water conditions; and third, the installation of casing to keep the hole open and permit measurement of the height of the water table over a period of years. With the single exception of hole 45, the drill holes are of the E-bit size, taking a core less than 1 inch in diameter and leaving a hole slightly less than 1½-inch diameter. The casing is 1-inch, galvanized pipe.

Water-level measurements have been made by electrical contact, using the pipe as a return lead, and passing the contact point down the hole on a light insulated wire carried on a portable reel with battery and a buzzer-relay which makes double use of the battery current. A score or more such measurements have been made weekly for the past 16 years and have yielded a large body of data. Under regular use, the reeling and unreeling of the wire produces a progressive stretching of several hundredths foot per hundred feet in the course of a few weeks, and recalibration of the critical length marks on the wire every 3 months has been found desirable. With this precaution, the rig gives a clear signal for water-table height to the nearest 0.01 or 0.02 foot, according to care in use.

Because of the superposition of hard, basaltic formations recurrently over weathered alluvium or loose cinders requiring casing, diamond drilling in Hawaii is difficult. This office was fortunate in securing for its early drilling the services of J. M. Heizer, who devised and applied methods which permitted drilling these small-diameter holes with a No. 11 Mitchell drill to depths of over 1,000 feet without change of drill or casing size. Aside from Mr. Heizer's uncommon judgment, caution, and adroitness, the success of the drilling rested on use of flush-joint casing wrung down but not driven, on the use of dynamite to open the drilled hole sufficiently to pass the 2¼-inch casing, and on the use of case-hardened bits. These methods have been continued by Harry Iwai, who had worked with Heizer, and with very gratifying success as compared with various diamond drilling operations attempted by a number of other drillers during the war. Failure to insist on case-hardened bits, failure to maintain hole gage, successive reduction in casing and bit size when difficulties were encountered, all but nullified the chance of drilling deep exploratory holes and restricted the evident abilities of most of the drillers to foundation testing, in which the operation was commonly stopped when a few feet of hard rock had been drilled.

TABLE 8

LOCATIONS AND PURPOSES OF DIAMOND DRILL HOLES

HOLE NO.	GENERAL LOCATION	DEPTH IN FEET	BOTTOM FORMATION	PURPOSE
1	Nuuanu, above Reservoir 3	128.7	Nuuanu basalt	Structure, valley fill
2	do.	204	do.	do.
3	do.	206.4	Koolau basalt	do.
4	do.	163.2	Nuuanu basalt	do.
5	do.	237	Koolau basalt	do.
6	do.	161	do.	do.
7	Nuuanu	422	do.	do.
8	do.	249.8	Nuuanu basalt	do.
9	Nuuanu, above Reservoir 3	457.6	Koolau basalt	do.
10	do.	423	do.	do.
11	Nuuanu	399.7	do.	do.
12	do.	424	do.	do.
13	Pauoa Valley	124	do.	do.
14	do.	156.5	do.	do.
15	do.	104.3	do.	do.
16	Nuuanu, above Reservoir 3	55.5	Nuuanu basalt	do.
17	do.	40	do.	do.
18	do.	63.7	do.	do.
19	West Kalihi	263.5	Koolau basalt	Basal water level
20	Kaimuki	201	Mauumae basalt	Structure, Waialae area
21	Waialae shaft	170.8	Koolau basalt	Basal water level
22	Waialae	152.7	do.	do.
23	do.	186.5	do.	do.
24	East Palolo	196	do.	do.
25	Waialae shaft	22.3	do.	Foundation data
26	do.	29	do.	do.
27	East Palolo	451.1	do.	Structure and basal water level
28	Nuuanu, Reservoir 3	26.5	Nuuanu basalt	Foundation, Aerator
29	do.	33.8	do.	do.
30	Nuuanu, Reservoir 4	171.7	Koolau basalt	East-end leak
31	do.	386.7	do.	do.
32	do.	92.2	Nuuanu basalt	do.
33	do.	98.1	do.	do.
34	do.	81.7	do.	do.
35	do.	88.1	do.	do.
36	do.	96	do.	do.
37	Palolo, center	299	Koolau basalt	Structure and basal water level
38	Palolo, west	325	Koolau	do.
39	Papakolea	184.5	do.	Basal water level
40	Palolo, west	518.5	do.	Structure and basal water level
41	Palolo, east	628.1	do.	do.
42–44	Numbers not used			

TABLE 8—*(Continued)*

HOLE NO.	GENERAL LOCATION	DEPTH IN FEET	BOTTOM FORMATION	PURPOSE
45	Nuuanu, above Reservoir 3	113	Nuuanu basalt	Structure, valley fill, and water table
46	Nuuanu, above Reservoir 3	165.7	do.	do.
47	do.	303	do.	do.
48	do.	437	do.	do.
49	do.	135.4	do.	do.
50	do.	155.5	do.	do.
51	do.	156.6	do.	do.
52	Pauoa, near Booth Spring	150.4	Koolau basalt	Structure, Pauoa fill
53	do.	169.6	do.	do.
54	do.	131.6	do.	do.
55	do.	106.5	do.	do.
56	do.	111	do.	do.
57	do.	124.8	do.	do.
58	Site of proposed building, Beretania to Lusitana Street, west of Lisbon Street	42	Punchbowl basalt	Structure, water level
59	do.	30	do.	do.
60	do.	28.7	do.	do.
61	do.	21	do.	do.
62	do.	41	do.	do.
63	do.	24.2	do.	do.
64	do.	35	do.	do.
65	do.	61	do.	do.
66	do.	61	Black cinders	do.
67	do.	45	Tuff	do.
68	Kalihi	349	Koolau basalt	do.
69	do.	312.6	do.	do.
70	do.	330	do.	do.
71	do.	348	do.	do.
72	do.	130	Kalihi basalt	do.
73	do.	290	do.	do.
74	do.	267	do.	do.
75	do.	348	Koolau basalt	do.
76–A	do.	643	do.	do.
76–B	do.	ca. 170	....	do.
77–A	Kalihi	615	Koolau basalt	do.
77–B	do.	151	....	do.
78–A	Kalihi	526	Koolau basalt	do.
78–B	do.	161.7	....	do.
79–A	Kalihi	425	Koolau basalt	do.
79–B	do.	ca. 150	....	do.
80–A	do.	265.5	Koolau basalt	do.
80–B	do.	ca. 150	....	do.
81	do.	493	Koolau basalt	do.
82	do.	402	do.	do.
		17,786		

Basalt, when sound and unbroken, is readily drilled by a diamond bit, but only rarely are these conditions found. In places where thick flows of ultrabasic basalt chilled in valley bottoms occur, unbroken rock has been sometimes encountered and in 8 or 10 instances single pieces of ⅞-inch core over 9 feet long have been recovered from the double-tube core barrel to the great satisfaction of the driller. More commonly the rock is so shattered or vesicular that breaks develop, and even where core recovery is practically 100 per cent the pieces average a few inches to 1 or 2 feet in length. All the cores from the drilling have been preserved, after transferring from field boxes to lighter, cardboard boxes with an inserted, wooden grid, and have been used in petrographic and other studies.

RESULTS OF DIAMOND DRILLING

The existence of a deep, secondary fill in Nuuanu Valley had long been suggested by the logs of artesian wells in the coastal area, by the behavior of artesian water, and also by the topography and rock outcrops in the valley bottom. The first series of holes was drilled to determine more definitely the transverse structure of the valley. Owing to the topography of the valley and to other considerations, the holes were drilled in the order and in the positions which at each stage would yield the most information. Locations of the holes and of the two geologic sections are shown in figure 11.

In the more inland section, five of the holes reached the Koolau rock at the bottom of the old valley. Because the two holes reaching the 400-foot elevation, over 400 feet below the present valley floor, are about 1,700 feet apart, it is quite possible that the deepest cutting of the old valley may be as much as 100 feet deeper; but the Koolau rock in the bottom of hole 10 somewhat limits postulating of greater depths.

In all the deeper holes, the lowermost portion, ranging in some to over 100 feet thick, consists of weathered, claylike alluvium or taluvium comparable to the material in deeper cuts in many parts of Oahu. It appears that after the great period of erosion there was some valley filling by sedimentary aggradation before the outbreak of late lava flows from vents in the valley. In the middle of the valley, the earliest of these flows poured out on a valley floor at about 350 feet below the present floor. In the section above this flow lie the cinders and cinder tuff of the Luakaha vent southeast of the lower Luakaha fall in Nuuanu Stream. Hole 7 passes through 300 feet of such material with lava flows only near the top. We do not know positively whether the early lava flow came from this vent before the eruption of the cinders or if it came from the upper vent, Makuku Cone, west of Reservoir No. 4 (plate XXII). There follow, in the valley section and forced to the west side by the slopes of the cinder cone, several additional lava flows, which mostly came from the Makuku vent. These are separated by layers of soil or alluvium which indicate that there were at least two, if not more, periods of activity.

The second cross section is based on three drill holes, holes 8, 11, and 12, with locations as shown in figure 12. In the easternmost of these, hole 8 near the Reservoir No. 2 spillway, the lowermost cinder layer overlies only about 30 feet of alluvium and is itself only 20 feet thick. Above it there is about 60 feet of late basalt probably corresponding to several of the intermediate flows of the upper cross section. This is overlain by another cinder layer and additional late flows. The alluvium at the bottom of this section is over 100 feet thick near the middle, and the Koolau surface at hole 11 is only 325 feet above sea level. From this known point the bottom of the rock floor passes downward to more than 800 feet below sea level at School Street. No exact data are available at intermediate points, but it is probable that the rock floor passes below sea level at some point near the Kimo Street bridge.

Later, additional information on the subsurface structure of Nuuanu Valley was revealed by several diamond drill holes in the area west of the highway and inland from the cross sections of figure 11 (holes 16, 17, 18, 45–51, inclusive). None of these holes reached the valley bottom, but they have furnished useful information concerning the upper structure of the late lava flows and also concerning the prevailing perched water table which furnishes water to Tunnels 3 and 3A.

The structure of Pauoa Valley between Kahuawai and Booth Springs has been explored by the drilling of nine drill holes (holes 13, 14, 15, 52–57, inclusive). These holes show that Pauoa Valley was cut about 100 feet below the present floor and that during the eruption of Tantalus a thick mass of cinders was deposited in it, especially on the side toward Tantalus. This cinder formation accumulated on the east wall of the valley and undoubtedly in many places cascaded into the axis of the valley at the angle of repose. Thus, in general, the topographic axis of the valley was shifted away from Tantalus toward Nuuanu Valley. In this new valley bottom were replaced at least two flows of Tantalus basalt, with the thicker and lower parts toward the west.

Booth Spring appears to be due to local perching of valley-bottom water on one of these lava flows; Kahuawai Spring is supplied from an extensive ground-water body in the cinder fill which is diverted to the surface either by narrowing of the bedrock valley or by some perching effect of interbedded Tantalus lava flows. The alluvial layer lying immediately over the Koolau bedrock is thin, hardly more than 10 or 15 feet thick anywhere, but it appears to have a large perching effect.

Several diamond drill holes (20–24, inclusive, 27) were drilled in connection with developing water from the Waialae area, No. 5. They have yielded valuable information on the elevation of the basal water table in this area, in relation to leakage from the Moiliili area, No. 1, and also have made it possible to determine a drawdown figure centering on Waialae Shaft (figure 15). Data from these holes will prove very useful in connection with the proposed extension of Waialae Tunnel and also in evaluating the effectiveness of the proposed recharge tunnel in Palolo Valley.

Holes 30 to 36 are located within a radius of 100 feet near the east end of the dam at Reservoir No. 4 in

Nuuanu Valley. They were drilled in an effort to determine the structure responsible for the so-called east-end leak. This leak is related primarily to the height of water maintained in Reservoir No. 4, and it is not clear that its exploitation is consistent with long-run policy in regard to mountain water sources.

Holes 37, 38, 40, and 41, combined with 27, form a nearly straight line across the inland end of the Palolo Valley bottom and have disclosed the geologic structure shown in figure 8. The valley floor here stands at just under 300 feet in elevation. The bottoms of the two branches of the rock valley are at least 200 and 300 feet below sea level, respectively, and the rock ridge between them rises to above sea level. Slightly more detail would be revealed by more holes, but the steepness of slopes between these points is such that the placing of these holes can be regarded as unusually fortunate. The lowest part of the section in each branch is the usual coarse, mottled, and weathered alluvium, the thickness reaching 200 feet in the eastern, or Waiomao, branch. The valley had been filled to this position, about 100 feet below present sea level, when the first tuffaceous material was deposited. This was followed by additional coarse alluvium which grades upward into finer-grained, tuffaceous alluvium. It seems plausible that the first tuffaceous layers are primary, air-laid material and that material from the same early eruption was reworked to make the finer, tuffaceous alluvium that was deposited when the valley grades, both transverse and longitudinal, were much reduced. Another 10 to 50 feet of coarse alluvium followed before the Kaau lava overran the valley in a flow at least ¼ mile wide. This was followed by more alluvial tuff and local, coarse alluvium to form the present floor of the valley.

The most striking result of the drilling of this cross section was to show that the artesian pressure underneath the caprock tongue declined systematically from about 25 feet on the Moiliili, or west side of Palolo Valley, to about 16 or 15 feet on the eastern side at hole 27. The aquifer was reached in some holes at nearly 300 feet below sea level, but the heads formed an ideal piezometric slope between 25 and 16 feet, thus indicating a true hydraulic relation between the two sides and the active flow of water from west to east.

SHAFTS AND TUNNELS

Three types of tunnels have been driven for water development in the Honolulu–Pearl Harbor area. One is to develop high-level water confined between dikes and another to develop basal water that stands a few feet above sea level and is in balance with sea water. A third type of tunnel is driven just below the level of water bodies perched in caprock formations. The salient facts about tunnels within this area are given in table 9. Data on tunnels on Oahu as a whole have been compiled by Stearns.

TABLE 9

WATER DEVELOPMENT TUNNELS

NAME AND LOCATION	TYPE	INVERT ELEVATION	LENGTH	DATE OF EXCAVATION	FORMATION	DISCHARGE
		feet	*feet*			*mgd*
Palolo tunnel (Waiomao branch)	High level	987	180	1920	Koolau,dikes	0.247 (1950)
Kaea tunnels (Pukele branch)	do.	1,130	100	1910	Koolau	0.0 (1920)
	do.	870	120	do.	do.	....
Manoa No. 1	do.	550	72	1923	do.	0.176 (1931–32)
Manoa No. 2	do.	555			do.	0.039 (?)
Manoa No. 3	do.	760	81	do.	Koolau, dikes	0.243 (1950)
Manoa No. 4	do.	850	100	do.	Koolau	0.0
Manoa No. 5	do.	ca. 850	25	do.	do.	0.0
Woodlawn tunnel	do.	525	120	1925	Koolau, tuff	....
Tantalus No. 1	do.	1,215	80	1927	Tantalus cinders	....
Tantalus No. 2	do.	1,175	250	do.	Tantalus cinders and basalt	....
Dowsett tunnels	do.	775	580	....	Koolau	0.014 (1932)
Nuuanu No. 3	Valley bottom	810	554	(*)	Nuuanu basalt and cinder	0.17 (1946)
Nuuanu No. 3A	do.	900	314	(*)	Nuuanu basalt	
Nuuanu No. 3B	do.	900	128	(*)	Nuuanu basalt and cinder	
Nuuanu No. 4	do.	1,027	1,799 (?)	(*)	Older alluvium	0.28 (1950)
Nuuanu No. 4B	do.	968	228	(*)	Older alluvium and cinder	....
Nuuanu No. 4C	do.	937	136	(*)	Nuuanu basalt	....
Pauoa tunnel	do.	720	100	(*)	Tantalus basalt	....
Kalihi, Gay tunnel	do.	502	3,000	(†)	Kalihi basalt, cinder, and older alluvium	0.04–0.09 (1932)
Kalihi, Gay-mauka tunnel	do.	650	1,202	1928	Kalihi basalt	0.04–0.06 (1932)

TABLE 9—*Continued*

NAME AND LOCATION	TYPE	INVERT ELEVATION	LENGTH	DATE OF EXCAVATION	FORMATION	DISCHARGE
Kalihi Orphanage tunnels	do.	600	250	1905	Kalihi basalt and old alluvium	0.0 –0.03 (1932)
C. and C., Kalihi No. 1	do.	720	320	(†)	Kalihi basalt	0.016 (1948)
C. and C., Kalihi No. 2	do.	740	225	(†)	do.	0.014 (1948)
C. and C., Kalihi No. 3	do.	800	350	(†)	Kalihi and Koolau basalt	0.061 (1948)
C. and C., Kalihi No. 4	do.	810	380	(†)	Kalihi basalt	0.031 (1948)
C. and C., Kalihi No. 5	do.	835	300	(†)	Probably weathered Kalihi basalt	0.043 (1948)
C. and C., Kalihi No. 6	do.	835	260	(†)	Older alluvium	0.0 (1948)
South Halawa tunnel	Random	780	1,030	1900	Koolau	0.015 (1932)
North Halawa tunnel	do.	680	2,300	1901	do.	0.030 (1932)
Aiea tunnel	do.	650	375	1898	do.	0.0 (1932)
Waiahole main tunnel	High level	724	14,567	1915	do.	33.96 (1948)
Tunnel A	do.	811	1,011	1915	Dike complex	
Tunnel B	do.	796 (?)	1,260	1915	do.	
Uwau	do.	799 (?)	(?)	1932†	do.	11.32 (1948)
Waikane tunnels No. 1	do.	800	2,635	1927	do.	5.27 (1948)
No. 2	do.	800	2,342	1929	do.	1.35 (1948)
Kahana No. 1	do.	800	1,975	1931	do.	4.25 (1948)
Waikakalaua tunnels	do.	750	4,000	1900	Koolau	0.0
Wailupe tunnel	Basal	ca. 0			do.	
B.W.S., Waialae	do.	6	67	1936	do.	0.44 (1950)
B.W.S.,Kalihi	do.	20	85	1936	do.	9.08 (1950)
Navy, Red Hill	do.	5	1,121	1942	do.	10.4 (1950)
B.W.S.,Halawa	do.	–2	919	1944	do.	9.23 (1950)
Navy, Halawa	do.	(?)	(?)	1936	do.	1.71 (1950)
Honolulu Plantation Co., Aiea	do.		total=100	1942	do.	2.52 (1950)
Hawaiian Electric Co., Waiau	do.	3	428		do.	
Ewa Plantation Co., Ewa	do.	–4	1,086	1936	do.	18.39 (1950)
U.S.A., Schofield	(?)	Wells		1936	do.	3.45 (1949)
Oahu Sugar Co., Waikele	Basal	3	1,140	1906	do.	2.04 (1946)
Oahu Sugar Co., Waikele	do.	7	290	1906	do.	

* Prior to 1921.
† 1922 or earlier.

HYDROLOGIC CHARACTER OF ROCK FORMATIONS

Test holes, drilled wells, and various tunnels and other excavations furnish information on the thicknesses, attitudes, and structural relations of various rock formations and hence on the geologic history of a given section or mass. They also provide a cross section or statistical sample of any one or more formations with reference to textures, porosity, and any other characteristics of direct hydrologic import. Drill holes yield many valuable data for sections not otherwise known; tunnels and other excavations are more revealing because of the opportunity for continuous visual inspection of a larger area, comparable to a small, clean, and continuous unweathered outcrop.

Formations of hydrologic importance are: (1) the main mass of Koolau lava flows, extending, as far as known, to 1,500 or more feet below sea level without significant change; (2) Koolau dikes and dike complex; (3) lava flows of the Honolulu series; (4) cinders and black ash of the Honolulu series; (5) palagonite tuff of Honolulu craters; (6) deeply weathered gravel, alluvium, or bedrock from any volcanic or other parent materials; (7) calcareous reef rock, beach rock, or other "coral" rocks.

Hydrologic features of the rocks include porosity, distribution of pore space, and permeability and patterns of openings causing it. Other qualities include stability of the rock texture and capacity to remain open, both in excavations and in the smaller openings adjacent to the excavations, and content of soluble constituents capable of being leached out by the water.

The main mass of lava flows of the Koolau Range, like some but not all other lava formations in Hawaii, has a fairly high porosity, variously estimated at 10 to 25 per cent. It is very stable against slumping or clogging and is subject to only limited leaching and effect on water composition. Its most remarkable features are the high general permeability, the thickness and extent of the permeable pattern, and the lack of any difference in vertical versus horizontal permeability discernible under prevailing conditions of water movement over large areas. The capacity of a rock or soil for transmitting water under pressure can be quantitatively defined as the rate of discharge of water through a unit cross section at right angles to the direction of flow if the hydraulic gradient is unity. The Meinzer index is the number of gallons per day flowing through a cross section of 1 square foot under a gradient of unity, hence 1 foot fall in 1 foot of distance (Meinzer, 1923, p. 44; 1942, p. 452). The permeability of the Koolau lava formation in a great many wells and tunnels is of the order of 5,000 to 20,000 gallons per day in the Meinzer index. Put in terms more readily used, various holes and tunnels yield 500 to 2,000 gallons a day per foot of drawdown per square foot of exposed area. Hydraulic gradients in the Koolau lava flows are chiefly of the order of 1 or 2 feet per mile, less than 0.001 (fig. 15).

However, in the course of the past decade, two stations, the Red Hill Navy shaft and tunnel and the Halawa shaft and tunnel of the Board of Water Supply, have shown that tunnels of 500 or more feet in length, driven in the Koolau lava flows, may encounter a permeability as low as 100 or 200 and yield as little as 20 gallons a day per foot per foot. In both of these stations more favorable permeability was found by further tunneling, with final average permeabilities raised to the range 300 to 500. Lacking an adequate test excavation, or driving tunnel in a locality and at an elevation fixed by other considerations, it is evident that tunnels driven nearly parallel to the attitude of the lava flows run a somewhat larger risk of not penetrating permeable members than would an equal footage of well boring driven normal to the structure.

Koolau dikes not over 3 to 10 feet thick in many places have been shown to confine water behind them at heads of 50 to 100 feet, hence, taking a 5-foot thickness, at a hydraulic gradient of 10 to 20. Leakage through such dikes is very slow, often less than a gallon a day per square foot in visible sections. Thus, disregarding occasional specific avenues of leakage, the Meinzer permeability index must be of the order of 0.1 or less, indicating permeability of 10^{-4} or 10^{-5} that of the Koolau lava flows. This low permeability holds, despite the presence of close-spaced columnar jointing across the dikes. Evidently at depth the joints do not open significantly;

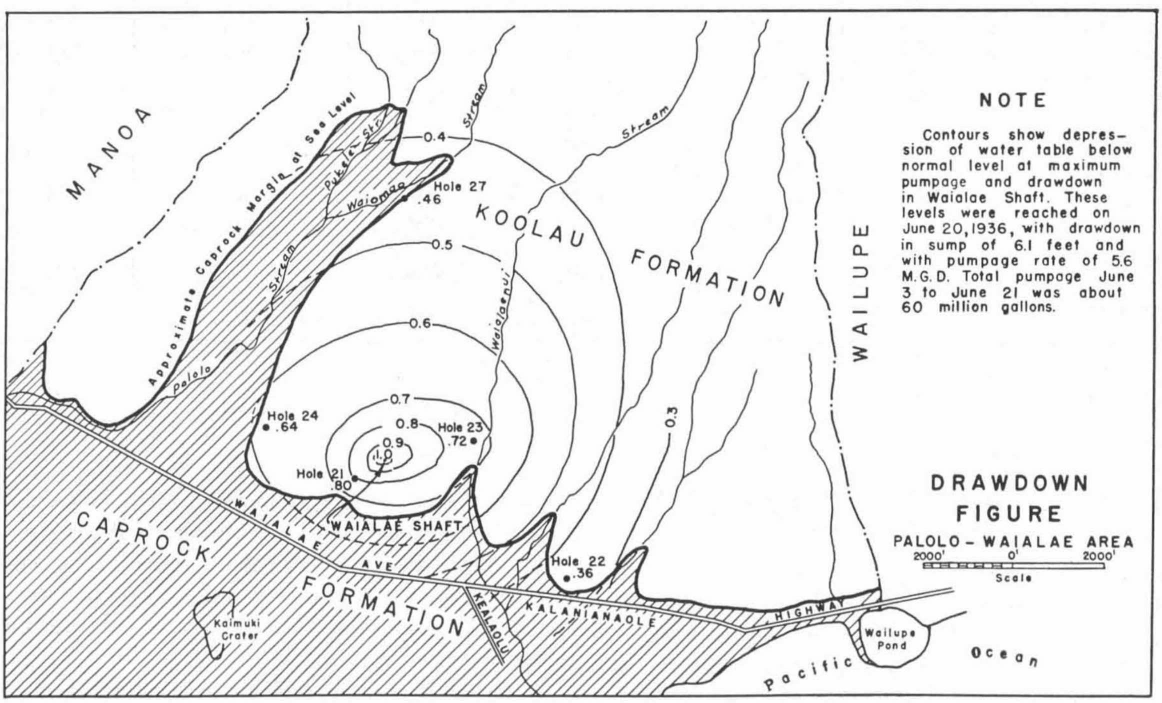

FIGURE 15. Drawdown figure surrounding Waialae shaft, based on a sump drawdown of 6.1 feet at a discharge rate of 5.6 mgd. Datum is the surface of the water table at no draft on the sump.

probably the opening of joints with approach to the eroded surface serves as an important control of the head of the confined water. A single dike, or a few dikes, with intervening lava flow structure, may provide very important high level storage and conditions favorable to water development. On the other hand at sea level, where there are small available head differences, presence of dikes is likely to be adverse to Ghyben-Herzberg functioning, and in parts of the dike complex with high concentration of dikes (probably anything above 2 or 3 per cent dikes) water development has not, in general, been practicable.

Lava flows of the Honolulu series are in the main interbedded with alluvium of the caprock, disposed in thick masses jointed in rather large blocks, or in other ways somewhat limited in structure and relation to large ground-water bodies. In general they probably have lower formation permeability or porosity than the Koolau series and they also are more likely to be invaded by weathering; the condition of hundreds of feet of thin and alternating layers of little-weathered aa or pahoehoe flows is not found in the Honolulu series.

In Nuuanu Valley, where flows of this series lie on or are interbedded with alluvium or other less permeable formations, they serve as avenues for movement of ground water but not in large enough or thick enough masses to facilitate regional measures of permeability.

The intrinsic permeability of cinder masses of the Honolulu series, where uncemented and unweathered, is high. Laboratory tests of undisturbed specimens have shown permeability above 3,000 gallons daily per square foot at 100 per cent gradient. Tests of larger masses in the field have not been attempted and observations in various tunnels have indicated that weathering of such cinders, variation in the bedding, and clogging by finer material prevail to such an extent that tunnels in cinders, except for very small local supplies, are less productive and less reliable than the better tunnels in lava flow formations.

Palagonite tuff is the result of alteration of air-laid volcanic ash to palagonite so that the grains are weakly cemented together. It is a weak rock, comparable to sun-dried clay, but it does not soften in water. The porosity of five Oahu tuffs averaged about 22 per cent (Wentworth, 1926, p. 104). However, because of the fine grain and formation of palagonite and secondary minerals, the permeability is very low and the yield of water under the force of gravity is very little. Tuff thus falls in the class of water barrier rather than aquifer. In the Pahala area of Hawaii, tunneling at the top of tuff layers has developed extensive water supplies, the water being perched above the tuff in the overlying lava flows of the Mauna Loa slope. It is a common observation in the Honolulu area that seeps and small springs issue at the top of tuff layers interbedded in the Koolau series, but none of these is of sufficient size to be practicable for development.

Weathered gravel, as well as any other deeply weathered basaltic material, including bedrock, has hydrologic properties of the utmost importance in the Honolulu water problem. The very general and extremely low permeability of the weathered basaltic residuum, whether from lava flows, tuff, or sedimentary derivatives, is due chiefly to the volume increase which takes place in the chemical weathering of such basic rocks. This weathering consists of oxidation, hydration, and carbonation of the various minerals of the basalt and results in an expansion by as much as 15 or 20 per cent. Since it is not so dependent on proximity to the surface as physical weathering, and takes place wherever air and water penetrate, it goes on through a rather thick zone from the surface downward. Moreover, the entire volume of the rock is involved; there are no minerals, such as the quartz of a granite, which remain unaltered.

Both the lava flows and sand and gravel formations in their fresh condition are porous and permeable materials with numerous large and small openings. However, such fresh materials are of rare occurrence near the surface. As weathering proceeds, the mechanical strength is reduced and the volume of mineral grains increases. The result is a self-ramming which closes all the larger openings. This is most effective at depths of a few tens of feet below the surface where the superincumbent load prevents relief of stress at the top. The most conspicuous examples of highly impermeable weathered basaltic flows or alluvium are in the lower parts of valley fills and of the coastal plain caprock where such weathered material has been under a load of some tens of feet of overlying material and is still subject to this process of expansion. In such material, all the larger openings, with dimensions of a half-inch or more, are closed. Only the smaller vesicles of a few millimeters in diameter remain open, and the vesicle pattern offers practically the only means of distinguishing between weathered lava flows and basaltic gravel. Since the pressure tending to close a spherical opening is proportional to the square of the diameter and the resisting cross section is proportional to the diameter, it appears that under any given pressure and strength of material there is a limiting diameter to openings that are competent to remain open and that all larger openings will become closed under cubic pressure. This principle also operates to close openings that are of great extent in one or two dimensions and to leave, of a given size, only isolated, compact openings such as vesicles, which would not be factors in permeability or effective porosity.

Since the weathering is promoted by access of air and water it is evident that it commences along the chief openings, and, in the event of shifting or deformation of the material, it would tend to be renewed at points where new openings might develop. It would be difficult to imagine a more effective scheme of sealing and resealing in any natural material. Where such material is exposed in cut banks it has a persistent tendency to remain moist and to retain its steep slopes and any tool marks that have been made in it. Where the sun and air have daily access, the surface dries and frays and such marks may disappear in 5 or 10 years; but in tunnels where the air is moist such marks appear fresh even after 30 or 40 years.

Measurement of the low permeabilities of these caprock materials is difficult, but it is easy to show that they are in the neighborhood of 1 gallon per day per square foot for 100 per cent hydraulic gradient. Eight tests by the writer showed values ranging from 0.14 to 2.8 in the same units. In round numbers it appears that the weathered caprock material has a permeability that is on the average about 1/10,000 that of the Koolau lava flows and perhaps inferior only to the Koolau dikes at depth.

The permeability of calcareous reef rock, or any other of the calcareous formations, is difficult to describe as a unit. In some places close to sea level, masses of reef rock have become cavernous through solution by ground water, and certain parts of the caprock near sea level yield water readily. However, these calcareous rocks are subject to change by solution and redeposition, and, except for the coral and coral sand layers near the surface of the coastal plain, there is no evidence that such rocks have high permeability. It is probable that the deeper coral layers revealed in the logs of drilled wells may be somewhat more permeable locally than the surrounding weathered alluvium. However, no such masses of continuity sufficient to serve as aquifers are known.

GROUND-WATER HYDROLOGY

GENERAL

Hydrology is the comprehensive study of water above, on, and in the earth; ground-water hydrology is the study of water in the earth. However, in restricted unit areas such as the islands of Hawaii, where the fresh water is derived from rainfall and eventually passes out to join the salt water of the ocean, it is impracticable to limit such study to water in the ground only. For our purpose hydrology includes study of the ground water itself and of its sources and its dispersal. The ground water is part of a great system of circulation; despite its persistence and apparent abundance in some places, it is nevertheless water in transit, and over any long period the amount moved cannot exceed the amount delivered from rainfall and infiltrated into the ground (Meinzer, 1942, pp. 1–8; Tolman, 1937, pp. 26–67).

The input and outgo of ground water can be expressed in the form of the hydrologic equation, where infiltration equals rainfall minus the sum of evaporation, transpiration, and runoff. This means that the water which enters the ground over a given unit area is the remainder after the evaporation, transpiration, and runoff are subtracted from the rainfall for the same area and a corresponding period. In Hawaii, and particularly in the Honolulu–Pearl Harbor area, the complete equation is somewhat more complex. The ground-water reserve carried in the Ghyben-Herzberg lens is very large, especially in the bottom portion. There are not only changes in the amount in storage in the top and bottom portions of the lens, but there is a continuous loss to the ocean which must be much less than it was when the prevailing head of the Beretania area was 40 feet or more. The whole equation is made up of the following terms:

ADDITIONS	DEDUCTIONS
Rainfall	Evaporation Transpiration Runoff Loss to ocean
Gain from top storage on falling head	Loss to top storage on rising head
Gain from shrinkage of bottom storage following historical lowering of head	Loss from increase of bottom storage, in event of historical gain in head
Gain by lateral transfer from adjacent areas of higher head	Loss by transfer to adjacent areas of lower head
Gain by transfer from shrinking bottom storage of adjacent area of greater thickness	Loss by transfer to increase bottom storage of adjacent area in event of historical gain in head
	Artificial draft

The following discussion undertakes an estimate of the reliability of the data we have on these factors and the practical use we can make of this equation. In principle it is equally applicable to the Honolulu and the Pearl Harbor watersheds. However, parts of the text deal chiefly with the Honolulu area because we have here more complete, or more comparable, data.

RAINFALL

The rainfall of the mountainous parts of the Honolulu and Pearl Harbor areas, like that of many leeward slopes in Hawaii, is largely made up of precipitation caused by passage of the prevailing trade winds over the crest of the Koolau Range and the consequent cooling of the atmosphere. The maximum average rainfall on this slope falls at about half to three quarters mile leeward of the Koolau crest, whence the amount declines rather regularly to reach minimum values along the leeward coast. The rainfall at the crest of the range is generally not over 80 per cent of the maximum in any given sector, with much local difference according to peaks and saddles (figs. 16 and 17).

This prevailing pattern of orographic rainfall is somewhat modified by the occurrence of rainfall of the convective type, due to differential heating over land and water areas, and also by rainfall connected with high- and low-pressure patterns which commonly move from west to east in the belt of westerlies lying north of the trade winds (Jones, 1939; Leopold, 1948). This belt remains somewhat north of the latitude of Hawaii, but is not far north. Moreover, since it takes its most southerly position during the northern winter period, pressure disturbances may at all seasons, and slightly more during winter, induce periods of weakened trade winds and lesser orographic rainfall. In some cases these periods, known as kona weather, bring heavy general or sporadic rainfall. These are the periods when persons in residential areas of Honolulu are most aware of rainfall; but such periods are, in general, of less significance in the production of intake rainfall than the normal orographic pattern.

The characteristic of rainfall which is of chief concern in connection with water supply is the nature and amount of its variability. For a unit such as the Honolulu area the variability of its total rainfall is of more significance than that of individual stations, and, since the underground storage capacity is large, the crucial variability is that which may affect periods of one or several years (Nakamura, 1933; Wentworth, 1946a). Probable variation in the Honolulu Intake Index, computed from 1890 to 1946, and based at present on 10 stations in the intake area, is shown in table 10 and also in figure 18.

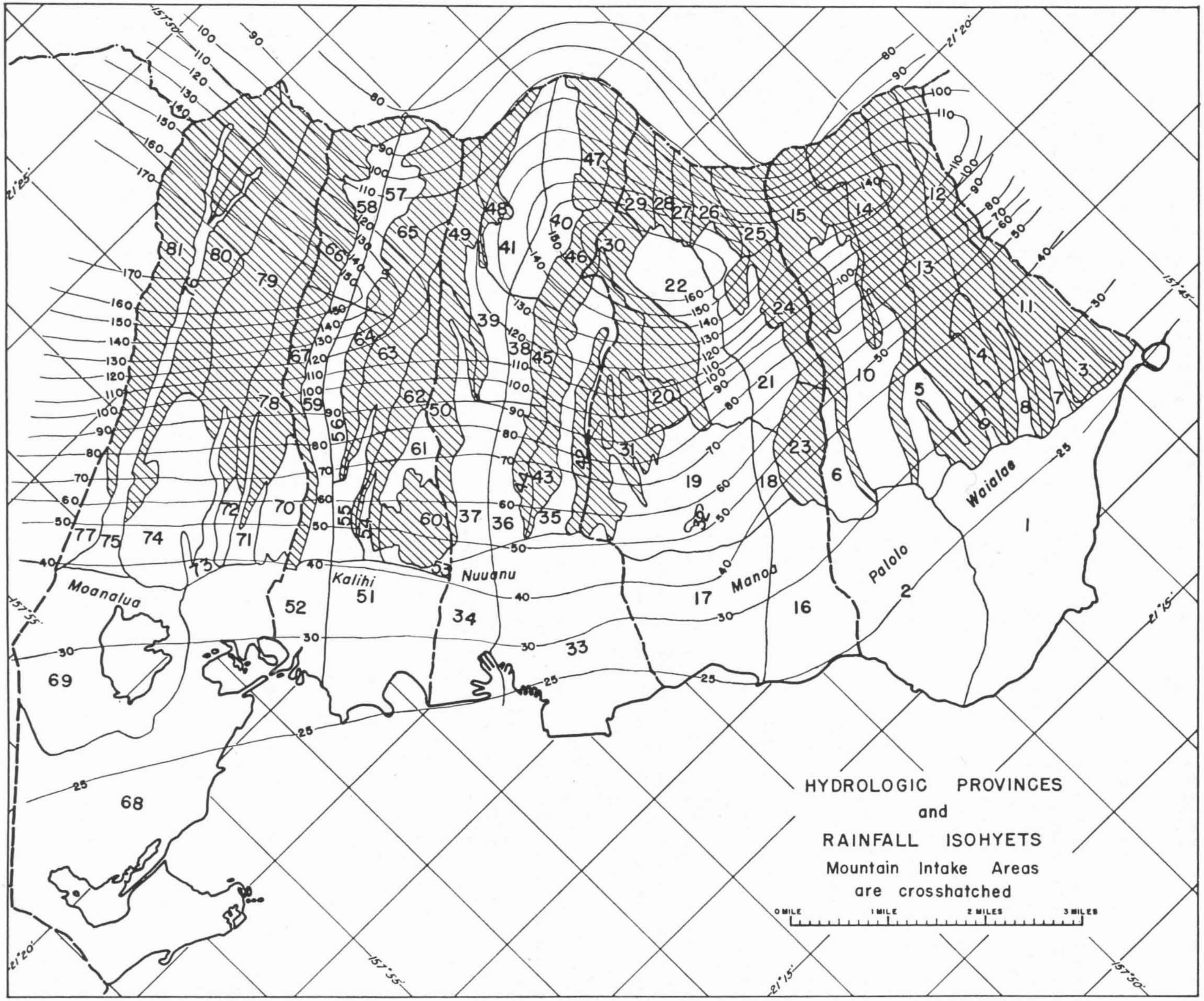

FIGURE 16. Annual rainfall isohyets and hydrologic provinces, Honolulu area.

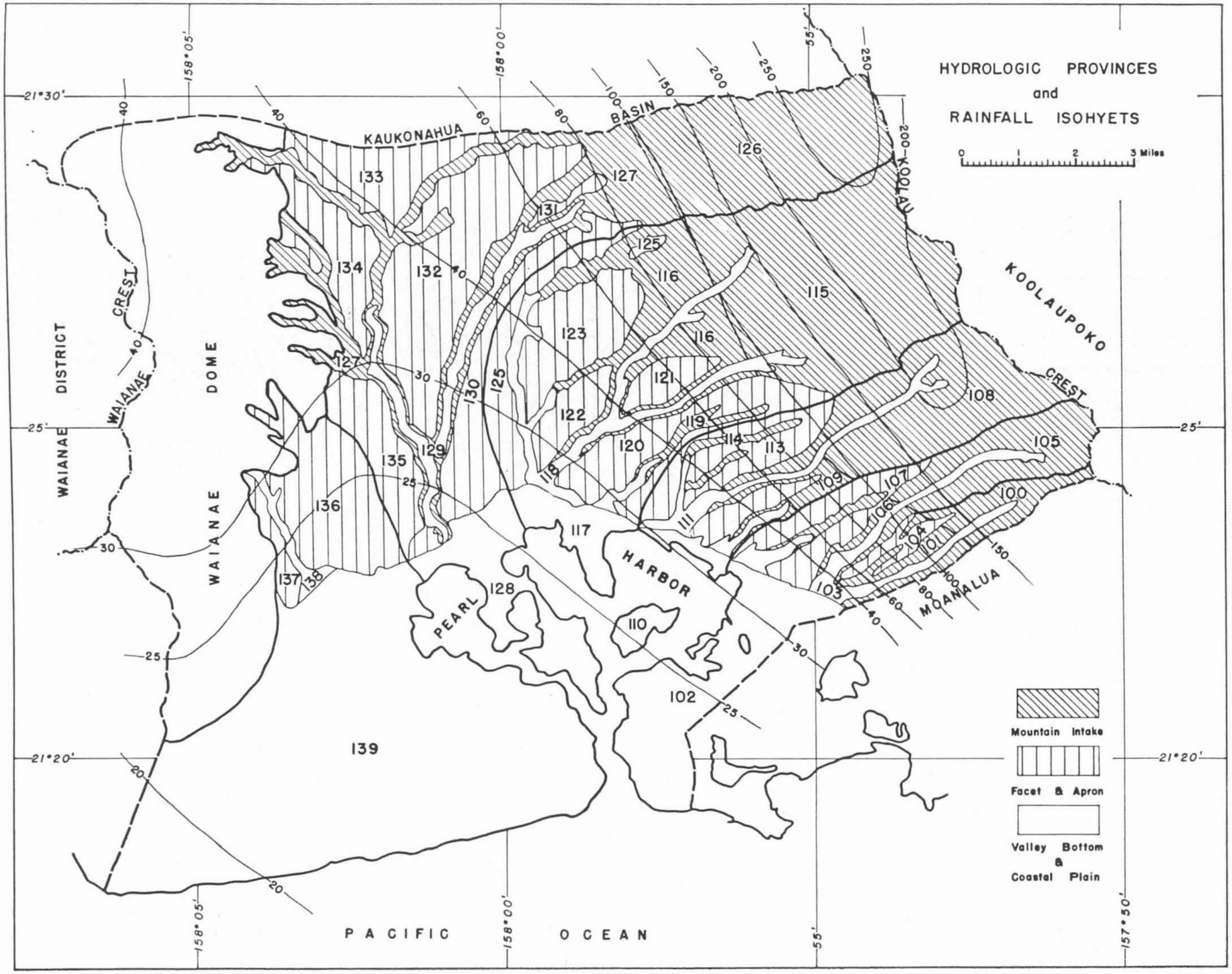

FIGURE 17. Annual rainfall isohyets and hydrologic provinces, Pearl Harbor area.

TABLE 10

PROBABLE VARIATION IN HONOLULU RAINFALL INTAKE INDEX

EXPECTED FREQUENCY	LOW ← PERCENTAGES OF NORMAL → HIGH									
	1 Month	5 Months	1 Year	3 Years	8 Years	8 Years	3 Years	1 Year	5 Months	1 Month
1 per 100 years	14	32	57	76	84	114	130	150	180	440
1 per 10 years	20	43	71	86	89	110	115	126	171	320
1 per year	38	61	. . .	. . .	. . .	. . .	. . .	. . .	143	190

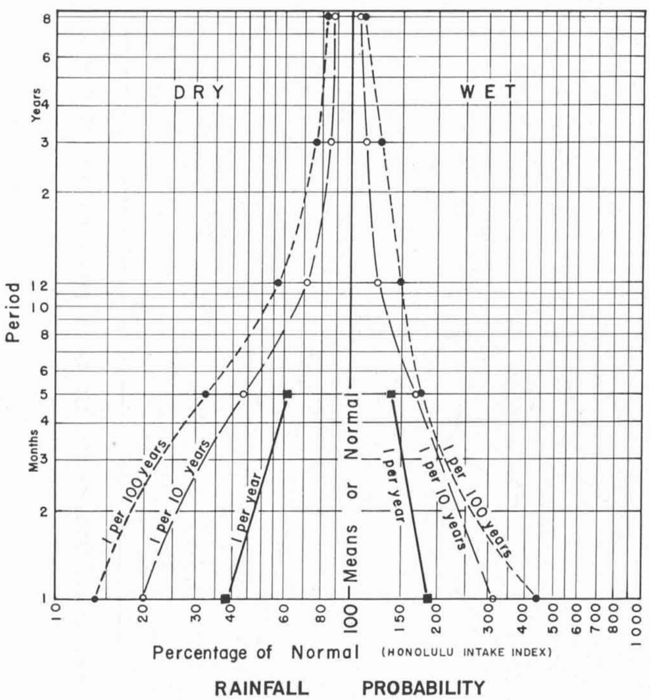

FIGURE 18. Duration-deviation probability diagram, Honolulu intake index. For example, this chart shows (on the left) that once per 100 years there is an even chance (as likely as not) that the rainfall throughout the Honolulu watershed area for a 5-month period will be as low as 32 per cent of normal (arithmetic mean). Or, on the other side, the probability is that once in 10 years there will be a 12-month period with as high as 125 per cent of normal. Various intermediate values can be read in the same way. Based on smoothed frequency data for about 60 years.

The figures in table 10 indicate that once in a century there is a 50–50 likelihood of a month as low as 14 per cent of normal and of a year that gets about 57 per cent of normal rain, but that the lowest 8-year period per century will probably have only about 16 per cent deficiency (index = 84). Periods of deficient rainfall shorter than 3 or 4 months are probably not clearly indicated in fluctuations of the water table, but longer periods, especially such as 8 years at 84 per cent of normal, can amount in the Honolulu area to a shortage of about 60,000 million gallons of rain, or roughly 20,000 to 30,000 million gallons of usable infiltration in the intake area. During such periods, by lowering of head, the deficiency is made up in part by (1) saving of natural leakage, (2) reduction of storage at the water table by some amount upward of 200 million gallons per foot of head lowering, and (3) reduction of bottom storage at an enhanced rate due to lowered head. The total daily deficiency in the probable usable infiltration over such a period is of the order of 10 mgd. The total value of (2) is slight; the important make-up must come from (1) and (3) in proportions that are not yet accurately known.

By accumulated use of comparative data, the variation characteristics of the rainfall are more accurately known than the absolute quantities derived from it. It is believed that the over-all measurement of rainfall rate for the intake area may be within 10 per cent of the true value, but the area of the intake area may not be known closer than 15 per cent. It is thought that the combined estimate of rainfall on the intake area is possibly within 15 mgd of the true value.

The geographic distribution of mean annual rainfall is shown on the accompanying isohyetal maps (figs. 16 and 17). These are based on data gathered by the U. S. Weather Bureau, by this office, and by other agencies and compiled by the Weather Bureau. In the calculation of cumulated quantities over periods of some length, the arithmetic mean appears to be most useful. On the other hand it is shown by various studies that the frequency distribution of rainfall totals for various periods, such as months or years, is commonly skewed, often approaching a logarithmic-probability distribution. Because of this, for certain purposes the representative rainfall of a given place is better indicated by the geometric mean or by the median, which is the most probable value for any given period.

For estimating the most probable rainfall in reference to agricultural ventures, the superiority of the median has been accepted by Halstead and Leopold (1948) in their recent compilation of monthly medians for the island of Oahu. After various studies of the distribution of rainfall totals, the writer feels that for an agency such as the Board of Water Supply, concerned most with total quantities for fairly long periods, the arithmetic mean has more practical utility as a representative figure, especially for large areas tributary to ground-water storage (Wentworth, 1947b).

TABLE 11

SUMMARY OF EVAPORATION AND TRANSPIRATION IN RELATION TO RAINFALL (BASED ON DATA COLLECTED MONTHLY)

STATION	PERIOD	INCHES PER MONTH (MEAN)			
		Rainfall	Evaporation	Consumptive Use (Transpiration plus Evaporation)	
				Ferns	Panicum
Luakaha (Nuuanu) 890 ft.	1931	12.06	3.97		4.17
	1932	15.02	2.85		
	1933	8.07	2.77		3.73
	1934	11.65	2.75		3.88
	1935	10.25	2.82		3.92
	1936	11.88	2.64		3.27
	Mean	11.49	2.97		3.79
Kaukonahua (Schofield Saddle) 1,250 ft.*	1931–32	26.36	1.29	1.96	1.86
	1932	24.12	1.36	2.04	1.78
	1932–33	17.37	1.19	2.19	2.04
	1933	14.44	1.22	2.05	2.30
	1933–34	12.00	1.68	2.57	2.46
	1934	15.11	1.59	2.96	2.51
	1934–35	17.73	1.49	3.16	2.59
	Mean	18.16	1.40	2.42	2.22

* Data for this locality are given by calendar years and also by years from September to August, inclusive. Hence, only 4 years total data.

EVAPORATION AND TRANSPIRATION

To evaluate the possible underground water supplies derivable from rainfall, losses by evaporation and transpiration, as well as by surface runoff, must be subtracted. Both evaporation and transpiration are variable according to the existing moisture pattern of a given time and place. Evaporation from a shallow pool reaches a maximum when the relative humidity is low and the air movement active. Losses under such conditions can be calculated, but the extent and duration of such conditions are difficult to define. On the other hand, in places and at times when the relative humidity reaches 100 per cent, evaporation reaches zero.

Unfortunately for the hydrologist, the variability of rainfall, both in time and space in Hawaii, together with the marked contrasts in elevation, ruggedness, and amounts and character of vegetation, pose an extremely difficult problem in estimating by whole areas and time intervals the total amount of evaporation or of transpiration. Transpiration rates are controlled in some degree by specific and ecological plant characteristics but are also fundamentally related to the humidity and activity of the air. Because the infiltration of rain water that is significant for water supply takes place chiefly in areas of moderate to high and variable rainfall and in areas that are mostly rugged and forest clad, it is the evaporation and transpiration from such areas that we would like to measure or estimate.

In 1929 an attempt was made to estimate evaporation and transpiration as quantities to be subtracted from rainfall in estimating infiltration (Kunesh, 1929). Evaporation was taken as 20 per cent of the annual rainfall for the whole area of Oahu and also for the Honolulu area, a conclusion based on existing data in texts and on a consideration of tropical conditions. Transpiration, on the basis of studies elsewhere (Kunesh, 1929, plate F), was taken as 30 inches of rainfall in all areas which received 30 inches or more and as the total rainfall in all areas receiving less than 30 inches annually.

Measurements of evaporation and transpiration were commenced in Nuuanu Valley at lower Luakaha in November, 1930, at a station installed by K. N. Vaksvik and maintained by the Board of Water Supply. A similar station was established at the elevation of 1,250 feet on North Fork of Kaukonahua Stream in July, 1931. The cover at the Nuuanu station was panicum grass, and at the Kaukonahua station both panicum grass and ferns were used. Detailed descriptions of both these stations and tabulations of data secured have been presented by the Territorial Division of Hydrography (Stearns and Vaksvik, 1935, pp. 202–213; Stearns, 1940, pp. 147–157). A summary of the data is given in table 11.

It will be noted that evaporation at the Luakaha station was over twice that at the Kaukonahua station, where the rainfall is greater by 50 per cent. This appears to be a consistent difference between the two stations, but such inverse correlation is not clearly indicated for different years at Luakaha and only very feebly so at Kaukonahua. The average evaporation value at Luakaha is about 26 per cent of the local rainfall and that at Kaukonahua only about 8 per cent. At both stations the mean transpiration value (consumptive use minus evaporation) is about 0.8 inch for panicum grass and about 1.0 inch for ferns. The mean of the values for evaporation is slightly under the 20 per cent used by Kunesh, and the 0.8 to 1.0 inch is much less than the 2.5 inches (30

TABLE 12

Discharge in mgd per Square Mile of Drainage Area,

Honolulu Streams

Name of Basin	Elevation of Gage*	Area of Basin*	Mean Discharge*	Discharge
	feet	*sq. mi.*	*mgd*	*mgd/sq. mi.*
Waiomao	373	1.0	1.33	1.33
Pukele	345	1.2	1.47	1.23
East Manoa	294	1.0	3.02	3..02
West Manoa	291	1.1	2.84	2.58
Nuuanu	632	3.4	5.80	1.70
Kalihi	464	2.7	5.20	1.93
Moanalua	339	3.2	2.65	0.83
Totals and Mean		13.6	22.31	1.64

* From: Territorial Planning Board, Surface Water Resources, 1939, pp. 17–53. (Measurements by U. S. Geological Survey.)

inches a year) used by Kunesh. However, these values must be recognized as taken under conditions far different from those of much of the mountainous intake area and can only be taken as suggestions that both evaporation and transpiration may be lower than values previously used. There is nothing to indicate whether evaporation as an over-all fraction of rainfall in the entire drainage area of Kalihi Valley (for example) down to the valley flats and edge of the coastal plain would amount to some percentage between 8 and 26 or a percentage outside this range. Neither does the fairly close restriction of annual means for transpiration by grass or ferns to 0.8 to 1.0 per cent give any confidence as to what the over-all transpiration performance of the forest and ridge vegetation might be. In the tables of complete data by months, consumptive loss has values as low as 0.36 inch per month and as high as 6.00, omitting some values that may have special explanations. These range from not over 3 to as much as 50 per cent of the mean rainfall. While it could probably be shown by statistical manipulation that the mean of monthly values at a given station has a probable error of less than 10 but more than 5 per cent of the mean rainfall, it is not known that anyone has a method of translating these tests or making others so as to estimate the actual, total area loss by evaporation plus transpiration with a probable error of less than some 10 to 15 per cent of the rainfall. This error would amount, in the Honolulu intake area, to at least 15 mgd.

RUNOFF

An important part of the rainfall is discharged as direct runoff. So far as the basal intake area is concerned, we need to know only the amount of the rainfall which is discharged as surface drainage across any boundary of the chosen area; it is immaterial whether some of such discharge has already been underground and has reappeared as stream flow, or if outside the basal intake area it is infiltrated into caprock ground-water bodies. It is clear that water discharged from a Koolau rock area in the upper part of a stream course is lost to basal intake if in the stream channel it passes onto a thick tongue of valley fill such as is found in several of our valley bottoms. Likewise, during heavy rains, water flowing off the Koolau spurs either to the surface of the valley bottom tongue or the coastal plain caprock is clearly lost from basal intake.

The net runoff from several major basins in the Honolulu area has been measured for many years, and there is only a roughly consistent figure for the mean runoff per square mile of the drainage basins themselves.

Table 12 shows quite large variations in the amount of runoff per square mile, and these are apparently only partly due to differences in mean rainfall. If we take these values to be individual attempts to measure the same value, i.e., the rate to be used for the part of the intake area that is included in major stream basins above the gage stations, we get the mean of 1.64 mgd. Also we find that the probable error of individual values is about 0.50 mgd and of the mean, about 0.20 mgd. But the above assumption is open to doubt and it is doubtful if we can consider the mean of 1.64 mgd to have an actual probable validity better than 0.50 or, possibly, 0.40 mgd. This would correspond to about 10 or 8 inches of rain.

The total area of these basins is 13.6 square miles. From intimate personal knowledge of the topography and geology of the watershed, an analysis has been made of the 81 hydrologic provinces shown elsewhere in this report. From this it appears that about 2.98 square miles additional to the actual gaged basins can be taken as comparable, and the remainder of the Honolulu intake area, or 8.36 square miles, as not comparable. Taking 16.58 square miles at 1.64 mgd per square mile and 8.36 square miles at an assumed rate of 0.82 mgd, gives a total runoff estimate of 34.05 mgd for the Honolulu intake area. It is thought that this figure is probably within 5 mgd of the truth, without bias as to whether it is above or below.

LOSS TO THE OCEAN

When the exploitation of the Honolulu ground-water body commenced in 1880, the artesian head of the Beretania area was about 42 feet. No doubt there were fluctuations due to seasonal changes, as now. We do not know whether the single record of 42 feet was average, high, or low for that time. We can only assume this as a rough indication of an approximate equilibrium, with the loss through springs on land and through submarine springs and seepage equal, on the average, to the amount coming from rainfall into the ground-water body at the water table. No large amount could be taken artificially without being provided for, either in increased inflow or in decreased outflow. No known sustained change in inflow has taken place; we can only assume that as the head is lowered and after the amount coming thus from storage has been used up, the natural losses for any extended period must have been reduced by an amount comparable to that taken artificially. It is stated below that possibly some water is still coming from the storage below sea level, but with this exception we can only assume that the natural leakage must be of the order of 30 or 40 mgd less than it was in 1880. Just how much has not been determined, but certain correlation equations for the Honolulu Areas 1 to 4 suggest that the change in amounts of draft available at different heads approximates 2.4 mgd per foot of head—very roughly, say, 2 to 3 mgd. Such a figure is derived from data chiefly in the range from 33 to 23 feet of head. We are not justified in relying strictly on a straight-line extrapolation to estimate the remaining leakage at 23 feet as 23 times 2.4 mgd, but we have no other basis for even roughly estimating this quantity.

It is a matter of practical observation at many pump stations that when heads are lowered the station capacity at a fixed head is increased; it is believed that the value of 2.4 mgd per foot in the operating range for the Honolulu area is probably within 20 per cent of the truth. But the estimate of about 55 mgd for total natural leakage at 23 feet of head is subject to greater uncertainty.

CHANGES IN STORAGE

By methods to be described elsewhere, rather consistent data have been developed showing that when the head in the Honolulu ground-water body goes down quickly there is a yield of excess water, and when it rises there is a deficiency in available water, each in relation to expected amounts. By combining some thousands of measurements it is found that the differences in draft under these conditions amount, in the Honolulu area, to approximately 200 million gallons per foot of head change (see below in this report). This result applies to calculations by monthly periods; when somewhat longer periods are used the amount is larger, corresponding, no doubt, to more complete drainage of the stored water. It appears reasonable that the practical amount of storage due to porosity should differ from any absolute amount according to the duration and completeness of drainage. At any rate, we can assume here that the ultimate storage at the water table is somewhat in excess of 200 million gallons per foot. In the event of rise or fall of the water table by a foot in 1 month, which approximates the maximum rate of change for such a period, the resulting deficiency or excess of draft due to the storage change will be slightly less than 7 mgd for such period. Since the maximum changes during a year are not over 3 or 4 feet, the amount available from water table storage during a year of such net change is probably not over 2 million gallons daily.

The doctrine of bottom storage has been set forth elsewhere in this report and need not be detailed here. However, unless some other acceptable explanation is offered, it appears that eventually the water carried in the lower part of the Ghyben-Herzberg lens must be accounted for in the shrinking of that part and the rise of its bottom to correspond to the lowering of the water table. The water table has been lowered by nearly 20 feet since 1880. The amount of water stored at the water table in a thickness of 20 feet appears to be somewhat in excess of 20 times 200, or 4,000 million gallons. Complete adjustment of the bottom of the Ghyben-Herzberg lens to this lowering of 20 feet would involve a rise of the salt water boundary by about 800 feet. There are reasons for considering the area of the transition zone to be much greater than that of the water table, and there are no reasons for believing the porosity of the rock to be less at the transition zone than at the water table. Hence it is considered a somewhat conservative estimate to take the 40:1 ratio for the storage quantities. But if we do so, the amount of storage in 800 feet of the aquifer would amount to 800 times 200, or 160,000 million gallons. The amount for each 40 feet, corresponding to completed shrinkage for 1 foot of artesian head loss is, on the same basis, 8,000 million gallons. Since even the latter amount is 22 mgd for a year, the conclusion seems unavoidable that even partial shrinkage adjustment of the bottom part of the lens can furnish continuously quantities of water that are significant fractions of the total water drawn. Unfortunately, we do not know the rates at which such water is drawn under different conditions of contemporary and past head lowering. Only some general limiting figures can be developed. These show that if the rate of shrinkage were so low as 1 mgd for an assumed condition of 1 foot unbalance of head, the shrinkage would be still very far from complete, and the fluctuations of the water table under seasonal differences of intake would be much greater than they are. On the other hand, if the rate were 10 mgd per foot of unbalance, so that after a sharp head loss of 4 feet there were 40 mgd of excess water coming in, the damping effect on seasonal fluctuations would be far greater than corresponds to actual observation. Such a rate would, in effect, drown out the artificial draft and tend to raise the water table at 2 or 3 feet a month. It seems fairly clear that the plausible rate of transfer of water from bottom storage to top storage lies between the figures of 1 and 10 mgd per foot of unbalance.

Since we do not know exactly either the rate per foot or, at any time, the amount of unbalance, it is clear that any estimates of momentary benefit from bottom storage are open to large uncertainty. For those who fail to accept the general principle, the amount of such benefit would be considered zero. At the maximum, under certain conditions, the writer thinks it likely that the benefit may be as much as 10 mgd. Estimates of this factor may perhaps be in error by several mgd.

TABLE 13

TERMS IN THE HYDROLOGIC EQUATION

ADDITIVE TERMS	SUBTRACTIVE TERMS	AMOUNTS		PRESUMPTIVE ERROR
		Gain	Loss	
		mgd	*mgd*	*mgd*
Rainfall on Intake Area		129*		15
	Evaporation and Transpiration		30†	15
	Runoff		34*	5
	Leakage to Ocean		40†	20
Reduction in Top Storage		2		1
	Gain in Top Storage		2	1
Reduction in Bottom Storage		10‡		10
	Lateral Leakage		5†	3
Totals		141	111	
	Draft Residue		30§	
		141	141	

* These quantities are considered to rest on measurements which, subject to the errors stated, give them independent validity.
† These quantities are estimates limited by certain known factors but consciously adjusted to provide an approach to plausibility in the whole equation. They are not even rough measurements.
‡ This value is conjectural.
§ This amount is clearly less than the truth for some years past; it results from the tentative character of the table, set up for illustrative purposes only.

LATERAL LEAKAGE

We have as yet no close determinations of amounts of water that may leak from one area to another under head differences. For the Honolulu district, Areas 1 to 4, the leakage between the component parts will cancel out; only the losses to Areas 5 on the east and 6 on the west will count in an estimate for the total of Areas 1 to 4. From the known behavior of all these areas we can for the present only conjecture that the loss may be of the order of 5 mgd, with possible deviation of, say, 3 mgd either way, under the conditions that have commonly prevailed.

Table 13 is an attempt to illustrate what we know about the terms in the hydrologic equation. The conclusion seems obvious that with the errors shown in certain terms it is quite impossible to adopt, by independent judgment, values for these terms which will yield a definitive residue for draft. Values used previously by Kunesh for evaporation and transpiration, when combined with the rainfall found on the more restricted infiltration area indicated by geologic studies, even without allowance for ocean and lateral leakage, give a residue which is already too small for the known draft.

But such a residue, being the total infiltration, is an amount which we can never presume to develop because it is quite unreasonable to suppose that the groundwater body is not subject to large leaks, both to the ocean and laterally. When allowance is made for such leaks in quantities consistent with collateral data, the residue is reduced practically to zero. However, when some allowance is also made for a yield of water from the bottom storage, the list of terms seems completed. That such storage is shrinking is shown independently by the slow increase of salinity in many wells, even when the head remains static for long periods.

The table serves two purposes: (1) to show the impossibility, as earlier stated by Hoyt (1934), of measuring or estimating all terms but draft, so as to yield, by the subtraction method, a reliable estimate of the amount continuously available to supply the artificial draft; (2) to show the qualitative interrelationship of the various terms in amounts adjusted to plausibly consistent orders of magnitude. In this respect the table represents a formulation that can serve as a framework for many different kinds of analysis in attempting to derive numerical values for quantities that cannot be derived by simple addition or subtraction.

OCCURRENCE AND BEHAVIOR OF GROUND WATER

SURFICIAL GROUND WATER

Surficial ground water, or what is called soil water by some, is water held in the soil and ground immediately below the surface. It is mostly water still susceptible of return to the surface by evaporation and by the growth of plants (Meinzer, 1923, p. 23). In Hawaii, where the rocks below the weathering zone are commonly open-textured, the surficial water is rather sharply limited to the soil and subsoil in the weathered zone. Under it and down to some water table at considerable depth, the little-weathered rocks, except locally, are dry. The surficial ground water is important because vegetation is dependent on it in most areas and from it comes much of the evaporation and transpiration.

In turn the vegetation cover exerts an influence over the weathering processes and thus has an important effect on the intake characteristics of much of the mountainous terrane. At one extreme is the rock channel or steep cliff where fissured and little-weathered rock may permit water to pass freely downward without opportunity to reappear. At the other is the cover of thick, weathered alluvium sufficiently impervious that water stands on it and causes it to remain moist practically at all times and to considerable depth. Such a mass probably does not transmit any significant amount of water downward. However, materials of intermediate quality are probably able on the one hand to absorb what may amount to several inches of rain and on the other to prevent it from becoming either runoff or immediate infiltration. In due course such water, according to slope and other condition, will be divided among evaporation and transpiration from the upper surface, infiltration into the underlying rock, and possibly also some contribution to runoff. To operate in this way the downward transmission of the water is undoubtedly retarded by many days and probably continues for a number of weeks following a period of pronounced rainfall. It is believed, also, that yield of water to the main water body in the Honolulu area may be strongly retarded behind dikes or other restraining members in the inland rock mass so that the mass effect from heavy rains persists through 4 or 5 succeeding months.

Direct artificial draft of water from the surficial ground-water body is quantitatively impracticable. This is because the surficial ground water does not form a widespread or reliable water table, and yield would come only by very slow seepage. The chief occurrence of surficial ground water is in soil-covered areas where the infiltration of water to deeper ground water is not active or immediate. Probably the larger part of the infiltration of rainwater to deeper layers takes place around the margins of areas of surficial water and in permeable rock channels, rock walls, and the like, where percolation can take place directly.

VAGRANT PERCOLATING WATER

Water included under this term is equivalent to that designated by Meinzer as "intermediate vadose water" (1923, p. 23). This is water which is moving or percolating downward or laterally in accordance with the structure of permeable rock, between the overlying zone of surficial water and the underlying water table, which is the upper surface of the zone of saturation. In some places where the downward or lateral movement of the vagrant percolating water is impeded, bodies of perched or confined water are formed. These are not strictly a part of the vagrant water but they may feed it or be fed by it. Where the water trickles downward through various openings so as to fall freely and not set up a definite water column, this condition is called vagrant percolation. If a column of saturation is set up with a definite head, this, if known, would be called confined or perched water.

Downward movement of water from the surface of the ground to the main or basal water table clearly must take place either by vagrant percolation or through confined water channels or columns. We do not know what part of the infiltrated water moves in definite, confined channels, but very few such channels are known. It is notable that extremely small amounts of water are met with, or could be expected, in a random traverse through the rock.

For example, if we assume the annual transit downward by infiltration of water to equal 50 inches of rain, this will mean a daily layer 1/7 inch thick. In a tunnel section 10 feet wide and 100 feet long (1,000 square feet), this 1/7-inch layer would amount to about 12 cubic feet, or 90 gallons. Ninety gallons a day is about 1 quart every 4 minutes, or 1 cup per minute. Such an amount would not show up at all in 100 feet of tunnel unless it were concentrated in one drip point. Apparently all the flow indicated could take place without being observable and we can hardly say that the bulk of the water does, or does not, flow in somewhat concentrated channels. This estimate is consistent with the observed lack or rarity of seepage in many tunnels driven above the level of basal, perched, or confined water.

In Hawaii, except for a few tuff beds on which water is perched, there is very little evidence of the diverting of water horizontally by rock layers of low permeability. Such diversion is a common condition in many parts of the world, and the arrangement of the Hawaiian lava flows, one on another as thin layers, at first suggests such possible interception of water passing downward. Field evidence, as well as data on water quantities and the conditions in wells and tunnels, shows that movement of this kind is relatively uncommon in lava flow formations. A few volcanic ash beds, occasional sills, and, rarely, a weathered zone or a soil layer may perch water above it; but only for limited distances does water follow individual lava flows. It appears that because of cooling joints and the breaking of lava flows into small blocks, the total mass is as permeable vertically as it is horizontally. In any given section, some lava flows are more permeable than others, and these flows tend to yield water into tunnels more rapidly than others. However, the water here comes from all the flows and the general permeability is so great that such differences do not exert any real effect in horizontal diversion for great distances. At any rate we do not in the Honolulu area know of any distribution or behavior of water which shows a significant amount of lateral movement before the water table is reached.

PERCHED AND CONFINED HIGH-LEVEL WATER

In places where percolating water accumulates in porous rocks above some impervious layer so as to saturate the rock and form a local water table standing above unsaturated rock, this water body is known as perched water (Meinzer, 1923, pp. 40–41). Layers of rock which perch water in Hawaii are (1) ash or tuff beds, (2) sills, and (3) soil or other weathered layers. None of these is of sufficient extent in the Honolulu and Pearl Harbor areas to support large bodies of perched water, though limited areas of (1) and (2) are found, particularly in the valleys from Waialaenui to Nuuanu. Probably the most conspicuous is the water body that supports the waterfall known locally as "Old Faithful" on the east wall of Nuuanu Valley. This is perched above a thick layer of basaltic tuff. At other places small seeps are found above tuff layers or sills but yield very small amounts of water and are marked only by a more vigorous growth of grass or shrubs.

Confined high-level water is found where percolating water accumulates behind or between dikes. In some instances the confined water saturates the rock to a height of 100 or 200 feet and we do not know how completely such bodies are held up by convergence or thickening of dikes below. In the Honolulu area there are two successful and presently operating tunnels driven through dikes into such confined water. Several others have been driven but either were failures or have not proved to be of permanent value. The leeward part and outlet end of the Waiahole Tunnel system is in the Pearl Harbor drainage area. This will be described later. Several tunnels have been driven to penetrate dikes on the windward or pali side of the Koolau Range; reference to these is made below.

Palolo Tunnel

This tunnel, at an invert elevation of 987 feet, is driven 180 feet into the west wall of Waiomao branch of Palolo Stream and penetrates a 4-foot dike, 50 feet from the portal. It was driven in 1920, had a flash flow of 1.5 mgd, and has since then ranged in mean annual flow from 0.15 to 0.37 mgd. During the biennium 1945–46, the mean was 0.17 mgd; during 1947–48 it was 0.34 mgd. It has been suggested that the discharge of this tunnel might be increased by driving farther in a direction to pass under Kaau Crater, but no decision has been made as to the operational soundness of this plan. A correlation of 6-month averages for rainfall and for discharge for this tunnel shows a gain or loss in discharge from this tunnel of 790,000 gallons for each inch of rainfall. Since 1 square mile-inch is equal to 17.4 million gallons, the tunnel is evidently getting the equivalent of one-half the rainfall of 1/11 square mile, or one-fourth the rainfall of 2/11 square mile. These areas are respectively about 1,600 and 2,250 feet square.

Manoa Tunnel No. 3

This is the only one of five tunnels driven in the eastern head branch of Manoa Valley which continues in operation as a part of the city water supply system. It was driven in 1923 at an altitude of 760 feet. There are two branches, and the total length of tunnel is about 190 feet. Several dikes were penetrated. The mean annual discharge of this tunnel ranges from about 0.140 mgd to 0.310 mgd, according to rainfall. The effect of discharge from this tunnel on the flow of surface water in East Manoa Stream was the subject of litigation commencing in 1935 (Board of Water Supply, 1937, pp. 136–140). By stipulation between the Bishop Estate and the Board of Water Supply the percentage of the flow of the tunnel which would otherwise have reached the stream channel was determined by actual test over a period of a year (Board of Water Supply, 1939, pp. 150–151; 1941, pp. 181–188). In this test it was found that 17.1 per cent of the tunnel flow was water that might otherwise have reached the stream and 82.9 per cent was developed water. A rough correlation between rainfall and discharge shows that this tunnel discharges about 575,000 gallons per inch of rainfall on the nearby gage. This is equal to about one-half the rainfall for an area of 1/15 square mile or one-fourth that of 2/15 square mile. These areas are respectively about 1,350 and 1,900 feet square.

The Waiahole Tunnel Project[5]

The Waiahole Tunnel was commenced in 1913 with the object of transmitting water derived largely from windward surface sources through the Koolau Range for use on the leeward slope. The main tunnel was completed late in 1915 and delivers water into the head of Waiawa Valley at an elevation of 724 feet. From this point the water is carried in a ditch which contours the south slope of the Schofield Saddle and extends several miles westward to reach the slope of the Waianae Range at an elevation of about 650 feet. In much of this area, the level of the Waiahole Ditch marks the boundary of sugar cane agriculture; above it are pineapple fields.

The Waiahole project is a combined project deriving ground water from tunnels driven into the dike complex on the windward side of the range and also surface water from windward channels that pass across its system of collection ditches. Additional water enters the tunnel along the 14,000 feet of the main bore. The water entering the main tunnel leeward of the crest is computed on the basis of weir readings in the tunnel at the line of the crest and at the leeward portal, the difference being the water entering this part of the tunnel. This quantity has approximated 6 mgd in recent years.

At the time the Waiahole Tunnel was planned, it was recognized by the designer, J. B. Lippincott, that large amounts of water might be developed in driving the first 2,000 feet of tunnel on the windward side of the range and also that a considerable amount of percolating water tributary to the leeward side might be encountered in the tunnel on that side (Lippincott, 1911). On the other hand, there is no indication, in the report cited or in any other written source known to this writer, of any knowledge at that time of the possible confining of water behind dikes, or of the existence of a dike complex, or of its hydrologic significance. The suggestion that water might be expected in the tunnel on the windward side would easily follow from observation of flowing, high-level springs. However, Mr. Jorgen Jorgensen has stated that he and perhaps others connected with the work were aware of this possible source of developed water.[6] At any event it is clear that the distinction between vagrant percolating water and water confined between dikes was not then generally understood,

[5]Only a brief discussion on this project is offered here, since it is mainly outside the Pearl Harbor drainage area.

[6]Personal communication, about 1939.

and it is certain that the geologic structure and hydrologic significance of the dike complex were not even suggested at that time. Experience in the Waiahole Tunnel, especially the large amounts of water encountered under pressure behind dikes, was a most vivid object lesson and suggested to many persons the possibility of development of high-level water by tunneling in other places. Not all the projects undertaken were based on sufficient study of geologic and rainfall conditions, and we know today that each area has its own specific features which must be taken into account.

The most important consideration in the development of confined high-level water is the distinction between the copious, initial flow under high pressures, based on rapid depletion of underground storage, and the steady, permanent flow which can reasonably be expected after a new equilibrium has been reached. With a short tunnel and a small drainage area, fairly steady conditions may be reached in 2 or 3 years, but in some of the larger projects decline in the rate of discharge may continue for a decade or more. In such projects very careful attention should be given to the question of how it is desired to use the accessible water. Only the most stringent emergency conditions can justify the discharge and use of the water as rapidly as it will run out; to allow the water to run out unused is not justified under any circumstances and is contrary to both private and public policy. In constructing such a tunnel project, the excavation should be completed as rapidly as possible, using as much of the water as possible, and bulkheads should then be placed so that the flow can be controlled. How the flow should be controlled involves consideration of present and future value in a manner similar to that in financial problems. If emergency conditions give the full flow of water an exceptional present value, it can be used to full capacity but with realization that the amount will surely decline and may reach values of one-third or one-tenth of initial amounts. On the other hand if preservation of the stored supply for as long as possible is important and if at the same time it is recognized that natural losses are greater at higher bulkhead pressures, there is need for close weighing of all the conditions to set up a program that will gradually utilize the stored water and reduce the rate of outflow to approach that expected on a permanent basis. Only continued operations over a long period will determine the steady rate that will permit balancing of annual or longer periods of high and low rainfall.

The total discharge of ground water from the Waiahole system has been increased by progressive extension of several development tunnels on the windward side of the range. In recent years the total flow from the windward tunnels has been above 20 mgd and that from the leeward tunnel section about 6 mgd, in addition to surface water that ranges from 5 to 12 mgd. The total area from which it is reasonable to suppose that rain water could reach the Waiahole system either as ground water or surface water hardly exceeds 6 square miles. The rainfall is above 200 inches per year but probably does not average 250 inches. The product of 6 square miles and 200 inches is about 57 mgd; the total yield from the Waiahole system has for some years been in excess of half that amount but it will probably not maintain that fraction. At the southern end of the same dike system, at Haiku, is a development tunnel now taking about 3 mgd, and a project just completed at Kahaluu will probably have a steady yield above 2 mgd.

At increasing expense for tunneling and pipe lines, it is probable that moderate amounts of additional ground water can be developed in the 5-mile stretch from Haiku to Waiahole and that some surface water can also be added; but the fact that the dike complex lies progressively farther to windward of the Koolau crest and that its exposed leeward boundary is lower than in the Waiahole section does not justify a very optimistic estimate. In the Waiahole portion, with high rainfall and favorable position of the dike complex, the water currently yielded from the ground approximates 5 mgd per square mile of supposed area of intake or something like 7.5 mgd per linear mile of Koolau crest. The present writer doubts if more than half of either of these rates can be reached in the 5 miles from Waiahole to Haiku, and it is believed that the area from which water can be taken at high levels is much less, probably not over 3 square miles, suggesting an ultimate total of less than 10 million gallons daily.

General plans for combination development and transmission tunnels to connect the Waiahole system with the city of Honolulu have been offered by Jorgensen (1918), Palmer (1921, pp. 95–101), Kunesh (1929, p. 132), and Stearns. For various details reference is made to the discussion of Stearns (Stearns and Vaksvik, 1935, pp. 444–451). He stated that the total water recoverable from the proposed Kalihi–Waiahole tunnel system might be as great as the then-shown recovery of the Waiahole system (ca. 33 mgd) but that a conservative estimate would offer a substantially lower figure. Kunesh in his report suggested considerably larger total figures for total tunnel yield from Kalihi to Waiahole. The present writer's belief is that the total high-level ground water to be developed by tunnel systems from Haiku to Waiahole, including the present Haiku and Kahaluu tunnels, will not exceed a permanent flow of 10 mgd.

As stated above, the full discussion of the Waiahole and Waiahole to Honolulu tunnel systems, existing and proposed, is outside the scope of this report. The preceding comments have been offered as a part of the text on confined high-level water, since small parts of the dike complex system border on the Pearl Harbor drainage area and a small fraction of the water is involved in the inventory attempted in this report.

Intermediate between known high-level water and true basal water is the elevated water body encountered in the Schofield Shaft. This stands at about 270 feet above sea level and represents saturation of the rocks down at least to sea level, since several holes were drilled to sea level from the pump room at 287 feet. In 1938 an effort was made by the U. S. Geological Survey to measure the elevation of this ground-water body by geophysical methods and to determine its limits (Swartz, 1940, pp. 56–59). Various conditions prevented carrying the resistivity measurements to the great depth of

10,000 feet or more which was necessary to locate the salt water boundary at the bottom of the Ghyben-Herzberg lens. It was, therefore, not possible to verify the 270-foot level of the water table, but measurements were made on both north and south sides of the Schofield Saddle sufficient to indicate that the high-level body lies in a belt about 2 miles wide extending southwestward across the saddle under Wahiawa and Schofield Barracks. It seems most likely that this water body is confined within some structure in the Koolau lavas, most likely dikes or dike systems, but we have no direct knowledge of such structures. On the east the water probably merges with the dike-confined water of the Koolau axis and is probably fed in large measure from it. On the west its escape may be somewhat impeded by the soil-covered surface of the Waianae dome.

The Schofield Shaft was dug in 1937 on a 30-degree incline and the floor of the pump room is at 287 feet. Wells were drilled from this altitude to sea level. The daily yield of this shaft in recent years has varied around 5 mgd. Static water levels range from 274 to 280 feet above sea level. At least two other wells have been drilled to this water body, but the output of these is comparatively small.

Another intermediate water body that is only incompletely explored is that indicated by several springs in the Waaloa branch of Manoa Valley. Investigation of this ground-water body by drilling and driving of tunnel was recommended in an earlier report (Wentworth, 1938–1945, Manoa–Makiki, pp. 140–141). It is evident that we have less systematic knowledge of such intermediate water bodies than of either basal or true high-level water.

FREE BASAL WATER

Around the leeward margin of the Koolau Range of the Honolulu–Pearl Harbor sector of Oahu, there is no part that fails to show a free water table standing at some elevation between 1 and 25 feet above sea level. This condition is found in wells and shafts that enter the Koolau rock at any point just inland from the contour where the base of the caprock rises above the level of basal water, and it extends inland from the margin of the range in the several spurs for at least 1 or 2 miles as shown by holes drilled either from the valley sides or from the dome surface at several hundred feet above sea level. A comparable static head to within one- to two-tenths of a foot is indicated all along the coast in the artesian wells that reach the aquifer down to as much as 1,000 feet below sea level, and these wells give more extensive data on the basal water body. We do not have data on the corresponding free water surface under the inner two-thirds of the range, on any given radius, and we can only conjecture what the condition here may be. The free ground water at 270 feet in the Schofield–Wahiawa area cannot be taken as indicative of conditions on a radius such as that of Kalihi or Moanalua, and lacking exploration by drilling in the head of the Manoa Valley floor, as planned, we do not know by what steps the basal water rises inland in transition to the confined water that we find at levels above 500 feet in the main dike complex, Waimanalo to Waiahole, and in subsidiary dike belts like that of Manoa Valley.

The free basal water, with the corresponding artesian water, is readily divisible into segments, each having a nearly uniform head as shown in table 14.

These areas have been called isopiestic areas, that is,

TABLE 14

Isopiestic Areas

Number	Name	Static Level December, 1946*	Barrier
			No specific structure known
5	Waialae	9.5	
			Palolo Valley fill
1	Moiliili (Kaimuki)	23.7	
			Manoa Valley fill
2	Beretania	25.3	
			Nuuanu Valley fill
3	Kalihi (Kapalama)	24.8	
			Kalihi Valley fill
4	Moanalua	22.2	
			Halawa Valleys fill
6	Pearl Harbor	18.6	
			Slope of Waianae Range

* Water levels are higher at present, 1950, but those given are probably more typical.

areas of equal pressure. There is some variation in the degree of equality among the areas. In Areas 1 to 3, inclusive, the variation in static levels in any one is very slight, not over 0.2 feet among all the artesian and basal wells or shafts, except for wells in which the head is abnormal owing to leakage or excess salinity of the water. In each of these areas, such levelness across perhaps 2 miles of spur between the valley fill barriers is in very striking contrast to the abrupt change of head of 1 or more feet across the ¼- or ½-mile width of the barrier. The term isopiestic is very well justified.

Slightly greater differences are shown in the Moanalua area, No. 4, especially since there is apparently a slight valley fill barrier in Moanalua Valley, and a much greater difference is found in the Pearl Harbor area. This area is much wider than the others and while there are several major valleys coming out to the margin of Pearl Harbor, there is very little evidence that the valley fill in any of these valleys northwest of North Halawa has sufficient depth to occasion a consistent difference in basal or artesian levels on the two sides. Both Halawa Valleys are barriers with about half of the fall of head from Area 4 to 6 occasioned by each. From Aiea to Waimalu Valley there is a gradual fall of nearly 2 feet in the basal head, and thence westward the head rises again at Honouliuli to nearly equal that at Aiea. Perhaps the most plausible explanation that can be given for this sag in the Pearl Harbor isopiestic level is that the several large Pearl Harbor springs and, possibly, other exposed spots in the Koolau aquifer lie in this stretch and the caprock is not so broad and not so effective in this middle zone as it is in the Halawa sector on the east or in the Ewa sector on the west. Thus the difference can be explained on the basis of relative effectiveness of the caprock; no valley fill barriers have yet been correlated with abrupt head differences.

It is evident that the head maintained in a given ground-water storage area, such as these isopiestic areas of Oahu, is an equilibrium based on the relative inflow from infiltration and outflow by natural leakage and artificial draft. The leakage may be to the ocean or to an adjacent area, or it may be reversed in sign and become inflow by leakage from an area of higher head. In the case of the several units of southern Oahu, there are certain intake areas whose rainfall reaches each of two ground-water areas; the amount of water reaching the continuous basal water table is determined by rainfall conditions. The inland part of the basal water table is not separated by the valley fill barriers themselves; water on any segment of the water table that is higher than adjacent segments would tend to spread to these adjacent areas.

Since the differences in level of the basal water in adjacent isopiestic areas are quite marked, it has been postulated by some that the areas might be separated by systems of dikes. No field evidence of such dikes has ever been found, and the chief cause of the separation is now generally accepted to be the relatively impervious valley fills which are known in some instances to extend downward to nearly 1,000 feet below sea level. Recently, exploratory diamond drilling, both in Kalihi Valley and in and near Waiawa Valley, has revealed that while basal water levels under the spurs are quite uniform and consistent for 1 or 2 miles inland, those directly under the valley fill are irregular and higher.

It appears that under the lowest part of the valley fill, inland from the point where the valley fill passes below the basal water level, the Koolau lava flows are probably weathered and less permeable than they are elsewhere, owing no doubt to the persistent weathering caused by percolating water falling from the lava fill tongue. There is evidence, both in Kalihi and Waiawa valley bottoms, that under and near the tongue of caprock filling the old valley section the Koolau formation is receiving water from the caprock tongue and is more weathered and less permeable than it is at a greater distance. Such a process probably operates to produce an axial section under each of the valley bottoms extending farther inland than the actual valley fill and forming a relative barrier between the basal water bodies of adjacent isopiestic areas. This condition affords a further and most plausible explanation of the observed differences of level (fig. 19).

Development of water by skimming tunnels from the basal water body commenced actively about 1935. A number of stations have been completed so that in the Honolulu portion, Areas 1 to 5, about 40 per cent of the daily draft comes from such stations, and in the Pearl Harbor area, No. 6, the percentage is approximately 30 per cent of the whole.

Hind-Clarke Tunnel consists of 145 feet of main tunnel with a shorter branch driven inland from a pit near the former Hind-Clarke Dairy. This operated on a basal water head of about 2.5 feet but is now filled in. There is no continuous record of discharge but the amount at times was about 0.4 mgd, with salinity at about 500 ppm.

The Waialae underground pumping station of the Board of Water Supply consists essentially of a sump excavated nearly to sea level, with 67 feet of tunnel driven at an invert elevation of about 6 feet. Tests have shown that only a very small fraction of the water comes from the tunnel. The static basal water level is currently, 1947, at about 9.3 feet and the draft is limited to about 0.5 mgd (at a rate of 2.3 mgd) by the salinity of 155 ppm set as an operating limit. Plans have been made to extend the tunnel length at this station by some hundreds of feet to permit exploiting an estimated 2.0 mgd or better, without the restriction imposed by the drawdown and salinity occasioned by the present station conditions.

The Kalihi underground pumping station is served by a sump driven nearly to sea level and by 85 feet of tunnel at an invert of 20 feet. As in the Waialae station only a small fraction of the draft comes from the tunnel. The station is currently supplying about 10 mgd on a 24-hour schedule, with salinity at 58 ppm and at a drawdown of approximately 1.5 feet.

The Red Hill shaft and tunnel of the U. S. Navy lies on the west side of the Red Hill crest and hence in the Ewa, rather than the Honolulu, land district. However,

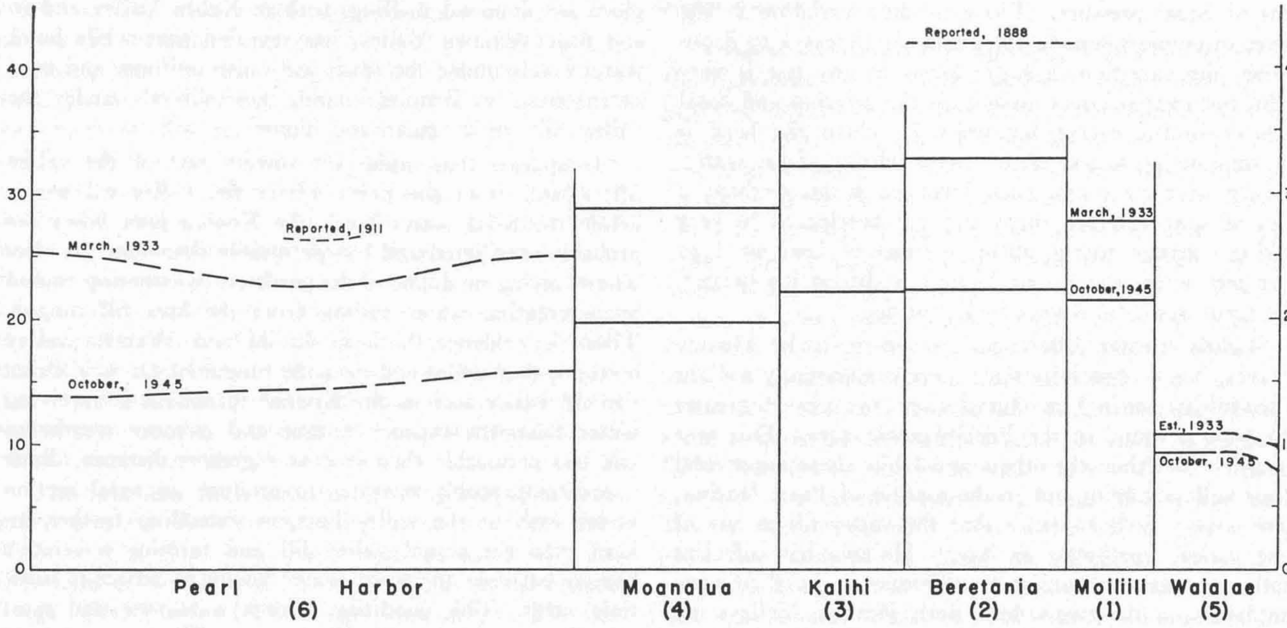

FIGURE 19. Diagram of maximum and minimum heads, Areas 6, 4, 3, 2, 1, and 5, with dates.

the boundary between the Moanalua and Pearl Harbor isopiestic areas is in Halawa Valley, west of Red Hill, and the Navy shaft therefore draws water from the Moanalua ground-water area. The sump of the shaft is driven below sea level, and the water is derived largely from 1,121 feet of tunnel commenced on an invert of 5 feet above sea level. Under a draft starting in 1943 and reaching a maximum of 20 mgd in 1946, the salinity climbed from 84 in 1944 to 118 in 1946. At a draft of 10 mgd and regional head above 25 feet, the salinity is currently about 90 ppm.

The Halawa shaft and tunnel of the Board of Water Supply is driven in the north wall of North Halawa Valley. It consists of an inclined shaft to reach a pump room with floor at 23 feet above sea level and a sump which extends to 18 feet below sea level. The development tunnel, starting at the pump room with an invert elevation of –2 feet, extends 919 feet in an inland direction at a grade of 0.5 foot per hundred feet. The current output of this station is about 7.5 mgd on a 24-hour schedule. The static salinity of this station has been determined at about 52 ppm; in the draft range from 7.5 to 15 mgd, the chloride content is 32 ppm and has shown no systematic change since 1945. This is one of the rare instances of a well or shaft in which salinity up to a certain point decreases with increase of draft.

The Halawa shaft and tunnel station of the U. S. Navy consists of an inclined shaft with sump and short infiltration tunnels. Following some reconstruction the tunnel has a total length of 248 feet and enters the sump with an invert of 11 feet. The current draft from the station is about 4 mgd and with salinity at 125 ppm.

The basal station of the Honolulu Plantation Company at Aiea is a vertical shaft driven from the elevation of 187 feet. The bottom stands at –6 feet and there is a total of 800 feet of tunnel. This station in recent months has drawn less than 1 mgd, with a salinity of 125 ppm.

The City and County of Honolulu drilled two wells from the elevation of 302 feet to the basal water in Aiea Gulch inland from the Honolulu Plantation mill. These holes are 16 inches in diameter, 10.7 feet apart, and reach 40 feet below sea level. They are not yet in regular use (January, 1951).

The City and County has a vertical shaft driven from the elevation of 111 feet inland from Pearl City. This shaft is expanded at the bottom by horizontal drill holes. The draft of basal water in recent months (1948) has varied from 0.25 to 0.50 mgd, with a salinity of about 120 ppm. Farther inland, with a curb elevation of 495 feet, is a deep well operated by the territorial Waimano Home. The draft from this well is small, with salinity at 24 ppm.

The Navy is constructing a basal shaft and tunnel in Waiawa Valley, and test holes were bored in 1948 and 1949 to secure data bearing on the exact location and design. In January, 1951, the tunnel, at a –4-foot invert, was 1,200 feet long and was yielding 25 mgd, of salinity 100 ppm, during construction dewatering. In the major valley west of Waipahu, formerly called Waikele Valley but now more properly Waipahu Valley,[7] are two basal tunnels 290 and 1,140 feet in length, respectively, driven by the Oahu Sugar Company in 1906. The longer of these has a yield of about 4 mgd. The invert elevations are 7 and 3 feet, respectively.

Ewa Plantation Company Tunnel, driven in 1939, has an invert level of –4 feet and is 1,086 feet in length. In 1948, with discharge around 15 mgd, it showed a salinity of 154 ppm.

In addition to the several basal tunnels described

[7]Decision of Geographic Names Board; letter from Max Carson, District Engineer, U.S. Geological Survey, to Robert D. King, Territorial Survey Office, October 22, 1943.

above, the free basal water is known through a number of basal springs, of which the series known as the Pearl Harbor Springs is the most conspicuous. In the Honolulu area the most important basal springs are those in the Kapalama section which have had an aggregate discharge of near a million gallons daily when the basal head of Area 3 is above 30 feet. Various other basal springs were known in the Honolulu area when the ground-water head ranged up to 40 or 42 feet, but these either no longer flow or at least have a much reduced flow not evident at the present surface as now graded and built over.

The Pearl Harbor Springs represent a large and mostly uncontrolled discharge of basal water as shown in the following table for a year when the head was near the minimum. Certain measurements have been discontinued and a breakdown for a more recent year is impracticable.

The geologic structure giving rise to these springs is very simple. The water stands in the little-weathered Koolau lava flow formation at the prevailing basal head, some 20 feet more or less above sea level, and is continuous with the artesian water in the same rock, which extends underneath the caprock for 2 or 3 miles farther toward the coast and to depths of several hundred feet below sea level. Seaward of the line along which the Koolau slopes pass below sea level, the Koolau rock is overlain by detrital and weathered caprock formations. These caprock beds also wrap around the Koolau formation to slightly above sea level and extend inland in the mouths of the several valleys which have been cut slightly below sea level. In the valleys the caprock is fairly thick, and even when the floor of the present valley is below the basal head there is little or no leakage. Similarly, on the upper slopes of most of the Koolau spurs the lava rock is weathered to some tens of feet to a rather impervious residual soil and mantle rock which passes below sea level and is overlapped by, and merged with, the caprock beds so that there is little or no leakage here.

It is mostly in positions between the major valleys and the main Koolau slopes, on the corners of spurs or in small alcoves where the caprock cover was originally thin or has been scoured by lateral cutting of some stream, that the Koolau fresh rock has either been exposed or the weathered surface part sufficiently thinned that the basal water can escape by gravity flow. Further scouring and increase of discharge have been caused both by the flow from such springs and by exploratory excavation at the spring sites. It is believed that the large discharge from these springs in the central part of the Pearl Harbor area where the arms of the harbor cut close to the range margin is the chief factor causing the head here to be consistently lower than that either on the east or the west, but there are probably other factors also.

The Hawaiian Electric Company at its Waiau plant has drilled a number of wells and driven an interconnecting tunnel to increase access to basal water in the vicinity of the Waiau Springs, and after some of the normal and augmented spring flow is used for cooling purposes at the power plant, it is pumped to higher levels for irrigation of sugar cane by Honolulu Plantation. As

TABLE 15

BASAL SPRINGS: PEARL HARBOR AREA (NO. 6), 1943–1944

SOURCE	OWNER	MEASURED AMOUNTS	LOCAL IRRIGATION	PUMPED IRRIGATION	PLANT CONDENSERS	DISCHARGE TO SEA	CHLORIDE
		mgd	*mgd*	*mgd*	*mgd*	*mgd*	*ppm*
Kalauao Spring	Honolulu Plantation Co.	15.3	?	1.4		13.9	69* 80† 154‡
Waiau Springs		6.1	?				138
Tunnel and Wells	Hawaiian Electric Co.	10.9					136
West Spring Group		8.7	?				
Pool	Hawaiian Electric Co.	11.7					
Total	(Hawaiian Electric Co.)	37.4		11.0 (Honolulu Plantation Co.)	36.4	26.4 (Kaluaoopu)	134
Loko Kukona		1.7	?			1.7	1,050
Puukapu		3.4	?			3.4	167
Waiawa	Oahu Sugar Co.	13.2	?	2.8		10.4	288
Waikele	Oahu Sugar Co.	8.2§	?	4.7		3.3	
Totals		79.0¶	?	19.9		59.1	

* At spring wall.
† At pump intake.
‡ At ocean discharge weir.
§ Based on measurements reported by Kunesh, 1928–1931; conditions believed to be similar in 1944.
¶ With exception of §, these are measured means for fiscal year 1943–1944, records by U.S. Geological Survey and Hawaiian Electric Co.

a short-term economy in the use of developed water, this is a satisfactory plan; but ultimate conservation requires that the discharge of all these springs be shut off and the water brought under control so that water not withdrawn for a definite use is retained underground and builds up the underground storage, subject only to the general hidden leakage which increases with increase in head. A recommendation in regard to effecting such control is set forth elsewhere in this report.

ARTESIAN BASAL WATER

The artesian basal water, together with the free basal water, constitutes the main body of fresh water accumulated from infiltration into the rocks of the Honolulu and Pearl Harbor sectors of the Koolau Range. This water is contained within the volcanic rock of the island and accumulates in floating equilibrium on the salt water which is continuous with the sea water of the ocean. According to the Ghyben-Herzberg theory, the fresh water, which is slightly more than 1/40 lighter than salt water, stands with about 1/40 of its volume above sea level and with the remainder below sea level. In parts of an island where there is no caprock and where permeable rocks extend both above and below sea level to the shoreline, the upper surface of the fresh water has the form of a low dome with steeper slopes near the shore and a flatter surface near the center. This form is a necessary consequence of the recharge by rainfall and discharge by flow down the slope toward the ocean. In response to this domed configuration and by application of the 40 to 1 ratio of the Ghyben-Herzberg principle, the lower limit of fresh water in such a simple island would be a deeply curved dome extending downward below sea level to a depth 40 times as great as the head of fresh water above sea level. This geometric form bounded by the flat dome above sea level and the deep dome below sea level and coming to an edge around the periphery of the island at sea level is the so-called Ghyben-Herzberg lens.

While there is much evidence to show that such a shape does really develop within small, nearly circular islands of simple rock structure, the form of the basal water body of the Honolulu–Pearl Harbor area is somewhat modified by the extensive and thick caprock which laps above and around the Koolau rock. This caprock forms the main coastal plain and extends inland in the over-deepened valleys of several of the principal streams. The retardation which this caprock offers to the escape of fresh water around the Honolulu and Pearl Harbor shore has the effect of causing the basal water to pile up within the rocks to heights of 20 to 30 feet above sea level. This in turn has resulted in the establishment of the sub-sea-level fresh water body to depths of more than 1,000 feet below sea level.

There is the further complication that the caprock fill which lies in several of the valleys extends some scores or hundreds of feet below sea level and remains below the level of basal water for 1 to 3 miles inland. As a result these tongues act as submerged weirs and cause persistent and nearly permanent differences between the basal levels of water in the aquifer on the two sides. The differences in level from one side to the other of such valleys range from 1 to 10 feet or more. While subject to change according to relative excesses or deficiencies in rainfall supply or discharge through artificial draft, they are nevertheless rather persistent and durable relationships even though general excess or deficiency may cause both levels to rise or to fall through a range of 5 or 10 feet. Recent studies in Kalihi and Waiawa Valleys suggest that there may be a weathered sector in the Koolau rock under the axis of certain valleys, inland from the caprock, owing to the effect of water percolating from the caprock tongue.

By far the largest amount of information concerning the basal water of the Honolulu and Pearl Harbor areas is that secured from artesian wells during the 70 years since 1879. Much of this information has been tabulated elsewhere and the present section will be devoted to a brief summary of the more salient facts. Because of the early success of drilling on the coastal lowland and the production of flowing wells, the goal of all the early water development was to secure flowing water. If a well were drilled from above the level of the artesian head and consequently failed to develop flowing water, whether that water were phreatic or artesian, the project was likely to be abandoned, and no data obtained on the mode of occurrence or the relation of the phreatic to the artesian water. Not until the past two decades has the driving of shafts or tunnels to the free basal water been a regularly recognized possibility in water development.

Fortunately, the free basal water and the artesian basal water are part of the same hydrologic mechanism and have, within narrow limits, the same head, so that the historic record of the artesian wells will merge with the future record of basal water with no significant break. Moreover, because of desire to develop fresh water along the coast, artesian wells were drilled to sufficient depths, 1,200 feet or more, to probe the Ghyben-Herzberg lens practically to its bottom. Along with the damage that has been done by such drilling and such overdraft, we should credit the great amount of information so derived and which we would not have, had the exploitation of the free basal water come first.

In the earlier period of exploitation, as elsewhere, the wells were allowed to flow freely, and in addition to the great benefit from flowing water a great share was wasted. Gradually it was realized that such waste would lead to lowered heads and other more serious consequences, and efforts were made to eliminate some of the waste. Within the first years after annexation in 1898, efforts were made by several people in authority to have studies of water supplies made by the U. S. Geological Survey, and in 1909 stream-gaging operations were started. The topographic mapping program started about the same time. There was from these early days recognition by a few persons that the chief mineral resource of the Territory is water; this was the underlying thought in developing the program of geologic mapping by the Geological Survey which is now nearing completion.

Our composite picture of each of the several sectors of the Ghyben-Herzberg lens in southeast Oahu is somewhat as follows:

1. The upper surface inland from the caprock is practically level, with slopes of less than 0.0001, and extends in each spur from the caprock tongue in one major valley to that in the next. Inland from the point where the bottom of the axis of the caprock tongue stands at the basal level (a few feet above sea level), there is probably a steepening of slope and a merging of levels as the surfaces of two adjacent basal areas extend inland toward the dike complex. To what extent the basal water level rises in steps behind successive dikes toward that complex is almost wholly conjectural.
2. The upper surface of the lens, seaward from the line where the base of the caprock stands at basal water level, has the slope of the base of the caprock, probably approximating the original or eroded surface of the Koolau rock of the spur between the major valleys. In a hydrologic sense the aquifer is the rock which is sufficiently open-textured to hold and transmit water, and its upper limit is at the base of an irregular, weathered portion of Koolau rock which hydrologically belongs with the caprock. To the best of our knowledge, this surface in the seaward portion is everywhere overlain by an effective caprock down to the lower limit of fresh water. The water lying under the caprock is under artesian pressure and is artesian water, though it is in origin the same water as that in the water body inland from the caprock and exhibiting a free water surface.
3. The bottom limit of the fresh water lens segment is the so-called transition zone where fresh water gradually gives way to underlying salt water. Where there is a caprock and nearly uniform artesian pressure we suppose that this under surface of the fresh water must be nearly level and run seaward to some line where it intersects the sloping base of the caprock.

   So far as our knowledge goes, the base of the fresh water extends inland under the free basal water at a depth below sea level of nearly 40 times the head of the basal water table, with some allowance for tardy adjustment. There is reason to suppose that in some places as we go inland the lava rocks at such depth are crossed by more dikes or that the margin of the dike complex may extend much farther seaward at this level; but we lack definite knowledge of such a structure.
4. The lateral margins of each fresh water lens sector must lie under the axes of the valley fills at the seaward end and be restricted vertically by the depth of such fill below sea level. Inland, the limit must follow up the steepest slope of the free water table from the point where the axis of the bottom of the valley fill emerges at the basal water level, since the vertical surface lying under this line is the practical divide between ground water moving to one side or the other side of the valley fill, and hence to one or the other of the isopiestic areas.

   We have reason, from studies in Kalihi and Waiawa Valleys, to conclude that under some valley bottoms, inland from the point where the base of the tongue of valley fill rises above basal water level, the Koolau rock may be more weathered and less permeable than elsewhere. It is plausible to suppose that this is due to prevalence of percolating water passing downward from perched water found in some parts of the valley fill, and it is clear that such a relatively impermeable sector would add its effect to the caprock tongue itself and extend inland the relative barrier between the adjacent isopiestic areas. How general this condition may be we do not accurately know, but the concept adds materially to our speculation on the causes of isopiestic areas.
5. The inland vertical margin is a zone that is probably quite irregular and separates free basal water from confined water. In the simplest case it might follow the shape of a single outer dike marking the beginning of dike complex and the confining of water; but in most places we suppose it may be rather indefinite and would perhaps, like the margin of the dike complex itself, be very difficult to mark even if we had extensive access to the underground structure and its water.

The artesian basal water consists of the seaward ends of all such lens segments as that just described. Data from artesian wells have given us more information concerning it than we have concerning the free basal water. Until recently the latter was largely conjectural from our knowledge of the artesian water. An attempt is made here to summarize the salient facts about the artesian water, rather than to present any detailed enumeration of artesian wells. Data on the history of drilling of the wells are given elsewhere in this report.

Commencing with the first well drilled in 1879, the occurrence of artesian water within the lava rocks of the southeast slope of the Koolau Range has been shown by nearly 500 boreholes. Everywhere on the lowlands of the coastal plain or of a valley bottom, the drill first penetrates weathered formations consisting mostly of detrital material eroded from the range, with minor amounts of late lava flows and ash formations. The whole of these weathered surface formations constitutes the caprock. In addition the upper few feet of weathered Koolau rock may also be relatively impervious and a part of the caprock. When this has been penetrated the drill reaches the less-weathered Koolau rock, and water under artesian pressure enters the well. The wells penetrate the aquifer from a few feet to 2 or 3 hundred feet in some instances. The configuration of the upper surface of permeable aquifer has been plotted from artesian well data, both for the Honolulu and Pearl Harbor areas (figs. 20 and 21). The surface is, in general, conformable to the somewhat weathered slope of the Koolau Range and extends from the basal water level near the inland margin of the caprock to around 1,000 feet below sea level along a line which roughly approximates the present coast.

The presence of artesian water has everywhere been demonstrated in the zone 1 or 2 hundred feet thick in the aquifer just beneath the sloping base of the caprock. Practically, no artesian well need extend far into this generally permeable aquifer; we therefore know that fresh water is found (or was originally found) to the 1,000-foot depth near the present coast where the base of the caprock is 800 or 900 feet below sea level. How-

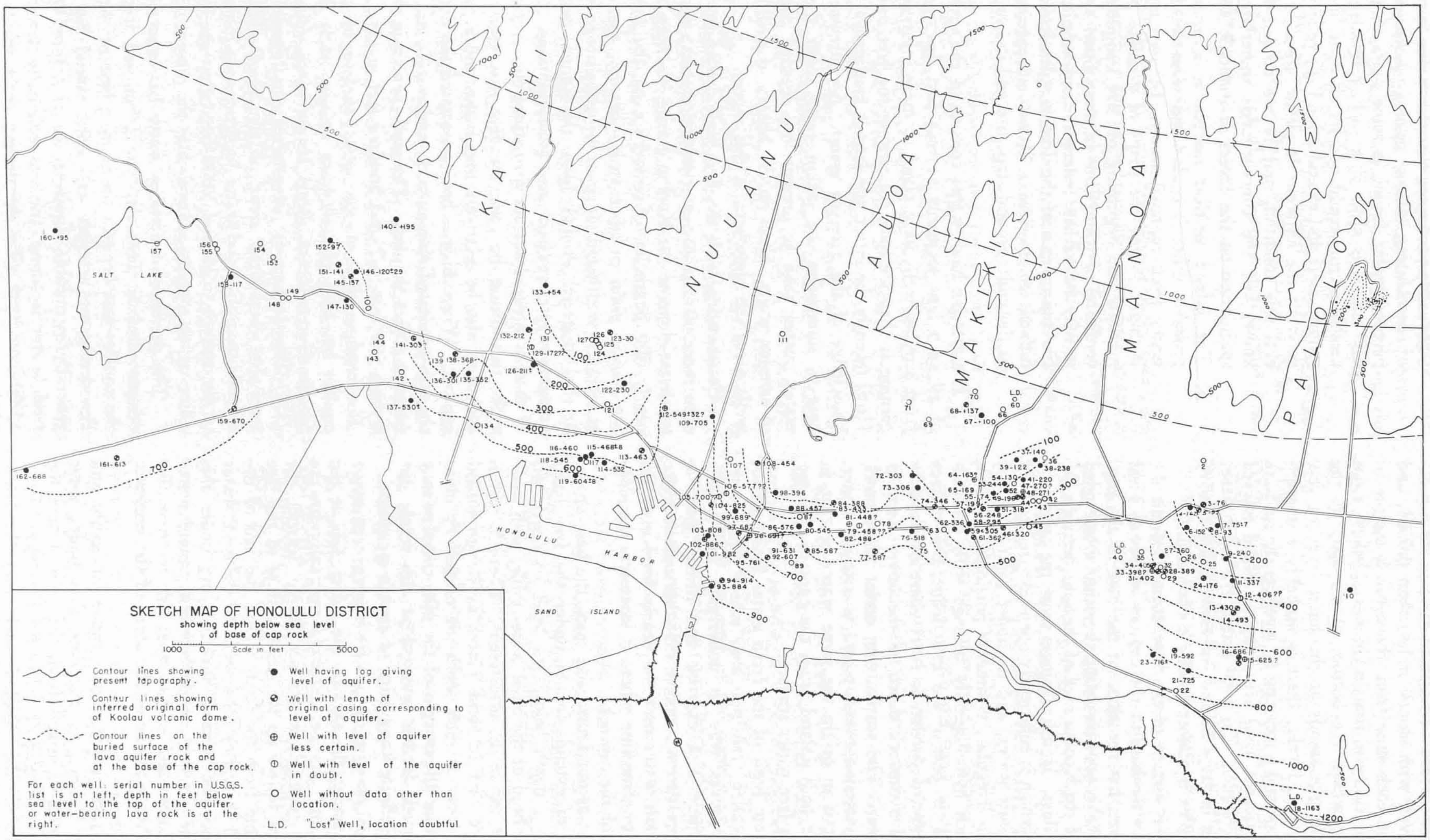

FIGURE 20. Contours on base of caprock, Honolulu area. Based on drilling records of artesian wells. In most instances the weathered top zone on Koolau rock, if any, is probably included in the caprock, so that the surface indicated may lie slightly below the original eroded surface. (Redrawn from Palmer, 1927, fig. 11.)

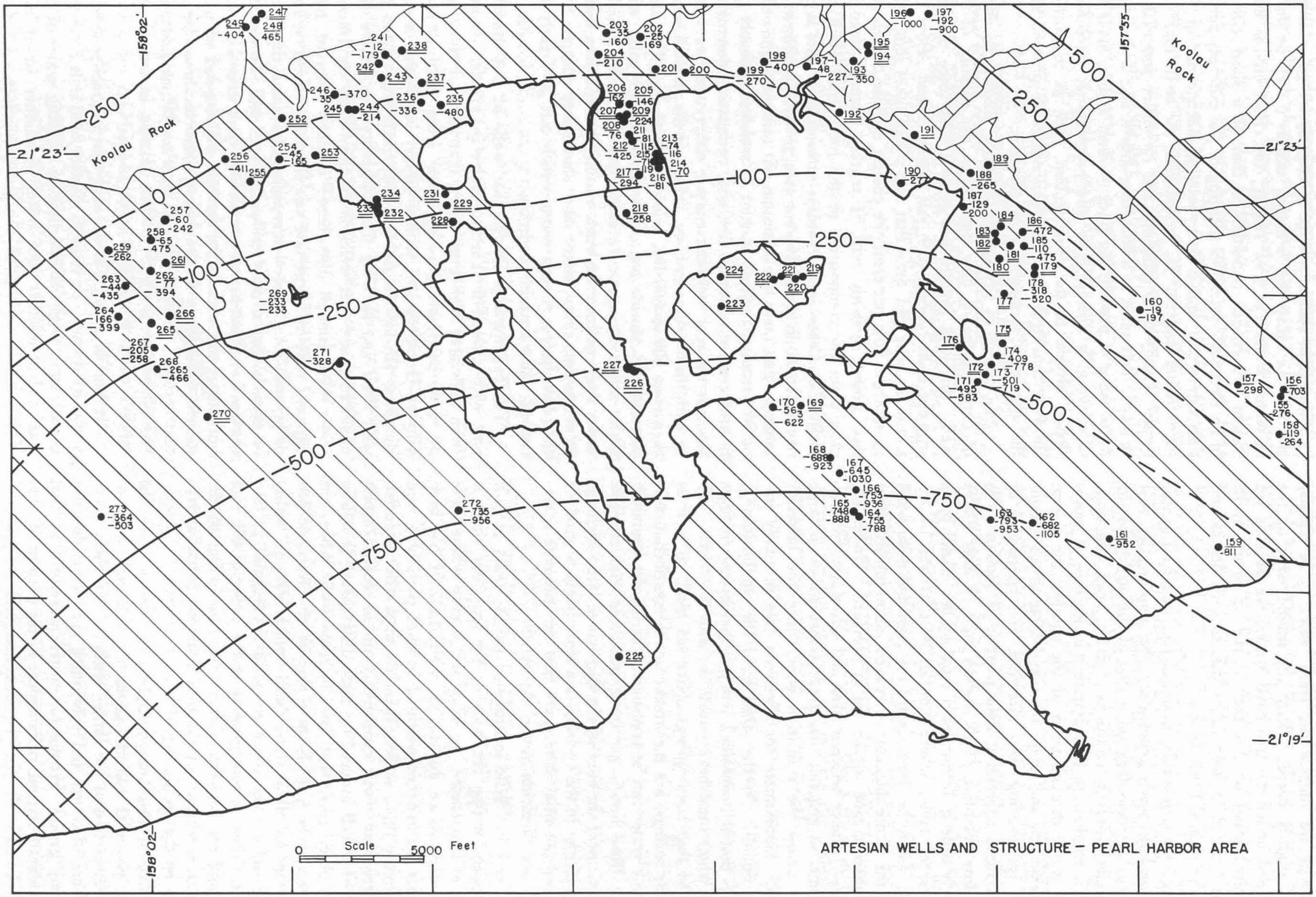

FIGURE 21. Contours on base of caprock, Pearl Harbor area. Based on drilling records of artesian wells.

ever, though we suppose the fresh water to be equally deep, or slightly deeper, along the inland edge of the caprock and under the free basal water, we have as yet only limited proof of this fact in the occasional wells which are drilled in deep valley fills to such depths and which have yielded fresh water.

Beyond the elementary, practical fact that fresh water is developed by wells penetrating the aquifer, the next most important consideration is that of the quality of the water under different conditions of draft, head, and time. First, it is emphasized that despite the slowness of movement of water through parts of the aquifer, the system is a dynamic one and under the water-table slopes obtaining and the existing size, direction, and continuity of openings there operates a field pattern of motion from high to low potential. This motion must in most places be a fairly orderly transmission from higher inland parts of the water table, where rainfall first arrives by infiltration, down the slope toward the coast and downward through the whole thickness by curved routes toward those places where escape to the sea is provided. Under the doctrine of balance between fresh and salt water, we cannot assume, in general, that fresh water passes in large amounts across the transition zone, since the behavior here must approximate that between two mutually immiscible liquids. On the other hand the equilibrium in quantities that is maintained requires that excess amounts of fresh water must have passed out into the ocean. We know also that basal springs above sea level, as well as submarine springs, are the breaks in the equilibrium surface where water can be transmitted across the boundary and that these breaks are more numerous and effective in the zone near the edge of the lens where large openings or irregularities in the openings are more likely to produce unbalanced potential differences that can promote movement in one direction across the zone.

We have but little information on the exact pattern of movement within the body of the lens, but there is one fact of importance. In many wells, even where there is little disturbance due to the well itself, it has been noted that the dynamic potential in some parts of a well may be more than, or less than, its geometric potential, and water may move consistently up or down certain sections of a well induced by these differences. It is also common observation that even in some wells which are not known to be leaking there may be characteristic differences in so-called static head which are in reality dynamic and are not consistent with any regular pattern of slopes. These are in general of the order of 0.1 foot or less and are probably due to the functioning of the well as an integrator of the total dynamic potential represented by the openings which it penetrates.

Because of this known slight deviation between the dynamic potential and the geometric potential, we conclude that certain of the larger openings and those openings whose direction and continuity are favorable offer sufficiently greater avenue for water movement so that these moderate irregularities appear in the pattern of head and, of course, also in the direction and steepness of hydraulic slope throughout the system.

Now if in such a matrix of slightly irregular slopes and flow an excavation is made, such as a well or shaft, in which water can flow readily, the effect on the flow system and on the potentials is that of a short circuit in an electrical system—a merging of the different potentials intersected and a corresponding disturbance of the surrounding pattern. If, in addition, the well, shaft, or tunnel is subject to pumping and its outlet potential is reduced, there must be a still more drastic and widespread disturbance of pre-existing lines to form a sink, made up of converging lines of flow and progressively steepening slopes, inverse to the cross section, such as to provide the flow consistent with the total difference of head and the aggregate permeability of the rock.

We cannot in any specific instance predict the effect of derangement of flow pattern on the salinity of the well. But it is nevertheless evident that since the lens segment is in contact with salt water at and below the transition zone and since that salt water takes some part in adjacent flow patterns, the change in flow can readily and almost certainly will, if marked enough, lead to changes in the composition of the total draft from the well. Experience in the various artesian and basal wells of the Honolulu–Pearl Harbor area, as well as elsewhere, indicates that there is a minimum salt content of the order of 20 parts per million of chloride which is probably the normal content of rain water after percolating downward through the rocks without contact either with sea water or with the basal water body. Many of the artesian wells, even from 500 or 600 feet below sea level, have furnished water with chloride content from 30 to 60 parts with little or no change over many years. Finally, under heavy draft or lowered head, various wells deliver water at increasing salt content and show very clearly that they have access to salt water which can be greatly increased under certain conditions.

The hypothesis is offered that wells of class number one, with around 20 parts of chloride, are fed directly from infiltrated high-level water, that wells of class two, 30 to 60 parts, are drawing water from the functional Ghyben-Herzberg lens with a quality based on the surrounding behavior of the lens with little effect from the well itself and showing much stability due to the size of the lens, and that wells of the third class are drawing water with enough disturbance of their own or from adjacent wells to be getting salt from the transition zone or beyond. In a general way it may be found that wells or tunnels that draw free basal water will show water of class I and that artesian wells will draw class II water, but this is not necessarily the case. A number of basal tunnels are known to draw water and to show changes that certainly indicate class II or class III, and artesian wells have drawn water of class II, that in some is susceptible of being modified toward class I.

It must be granted at the start that in practice there is a gradation from one class to another, and it is clear that certain wells might at one time be drawing water of one class and at another time water of another, or of both. This possible mixing of sources and effects, far from discrediting the concept of three classes, goes far to furnishing the decisive data for such a view. Using such a theory, the freshening of such stations as Halawa and Kalihi shafts with increased draft is explained as a change of the water from class II back toward class I, a change which is relatively much less common than that from class II toward class III. Further, in such situations as the south shore of Molokai near Kaunakakai, the basal water is of unstable and increasingly saline quality because in all probability the core of water of class II is either non-existent or does not extend out to the points penetrated by wells or shafts dug from the coastal margin. The water obtained is of class III. It is consistent with such a doctrine that in an island such as Molokai the fresh water lens may be so thin or so restricted that it does not exhibit the stability of water quality to provide a reservoir of water of class II. Whatever the cause, at the coast near Kaunakakai, the water encountered is class III. Farther east the water approaches more nearly to the postulated quality and behavior of class II, but could also possibly be class I.

CAPROCK WATER

The series of water types from rainfall to surficial ground water to vagrant percolating water to basal water is a complete series. In some places water is also perched on flat-lying impervious formations or confined between such vertical members as dikes. Likewise, some water on its way from rainfall to the ocean may be infiltrated into caprock formations, either of the coastal plain or of valley-filling tongues; this is called caprock water. In the valley tongues such water may be in ground-water bodies which are often shallow with reference to the surface of the valley floor or lateral fan slopes and which are perched in relation to the main basal ground water. The perching formation is commonly the thick trough of weathered alluvium and detritus which lines the bedrock surface of the deep valley and lies below the later valley fill. In some valleys, such as Nuuanu, the later valley fill consists of late volcanic formations, both lava flows and ash and cinder formations. These formations everywhere constitute the aquifers in the valley section, and in Nuuanu Valley, at least, there are two levels of such aquifer formations separated by relatively impervious layers of intermediate alluvium or residual soil. In such case they may give rise to two or more perched water bodies with orderly water tables one above another.

Few if any valley-floor ground-water bodies of any consequence are found in valley fills having no late volcanic constitutents, the fill consisting wholly of weathered detritus being chiefly a water barrier. In a few places the water tables within the valley section have sufficient slope and fall from the area of intake so that a slight artesian pressure may develop under tight impervious surface layers, but this is of practical significance only in a few places. Diamond drilling completed in 1950 in upper Kalihi Valley revealed an area of 25 or more acres beneath which there is a small artesian body having heads above ground surface so as to give artesian flow. The maximum head exceeds 60 feet above the ground surface. The water is perched on the trough of weathered alluvium in the filled valley and is apparently carried in the fractured and clinkery bottom part of the Kalihi lava flow which lies on the old alluvium. The restraining member above the water body is apparently the dense, main portion of the Kalihi lava flow, since that flow is exposed in many places along Kalihi Stream channel and shows no conspicuous escape of the artesian water; this, despite the fact that lava flows do not commonly form water barriers in Hawaii. The amount of water available from this body cannot be accurately estimated until a large-diameter well is drilled for a yield test and until observations can be carried over at least 1 or 2 years.

The valley-fill water tables respond very promptly to increased rainfall—those near the surface within a few hours and those at a lower level within a week or two—fluctuations of level being of the order of 2 to 10 feet between wet and dry seasons. Much of this water is high in carbon dioxide, and its use in various gravity parts of the Honolulu system has entailed problems of corrosion and red water which are somewhat troublesome because of the comparatively small amounts of water to be treated at any one place. The various tunnels and springs yielding caprock water from the valley fill have been described elsewhere in this report.

In the coastal plain portion of the caprock, particularly those parts made up of coral detritus, there is commonly a body of fresh or brackish ground water which has a water table of about 2 feet above sea level. This level represents a surcharge of land water against the ocean level which is sufficient to discharge the amounts that are daily added to the water body. The caprock water is derived from infiltration into the surface either in valley floors or on the coastal plain, from basal water where it rests against caprock around its margin just above sea level, and from artesian water which works upward under pressure. In a few places, as described above, the basal water escapes in large basal springs at levels showing its immediate source; in others, artesian water may reach the surface or come up under the sea so copiously as to show its origin.

Neither of these would be called caprock water, but other smaller losses from artesian and basal water become merged in the caprock aquifers with a head of only 2 or 3 feet and are true caprock water. It is doubtful if any considerable part of the coastal caprock water is derived directly from rainfall in the mountain intake area and it is mostly not closely connected with the perched caprock water of valley floors.

The caprock water of the coastal plain is mainly in balance with sea water and extends a corresponding distance below sea level where suitable rock permeability exists. However, since most of this water is somewhat brackish and is not of potable quality, the relation of quality to depth has not been explored in detail. The wells and shafts which penetrate it commonly draw progressively more saline water with increase in rate of draft as would follow from proximity to the salt-fresh theoretical boundary. The consistently low head over the coastal plain area where deep wells reveal artesian water with heads of 15 to 30 feet at different times in various areas shows the complete general separation that exists between the caprock water and the artesian and basal water.

THE MECHANICAL TESTING PROGRAM

In 1934 the suggestion was made by Simes T. Hoyt that the pumping plants of the Honolulu water supply system be used in a series of tests to determine a number of hydraulic characteristics of the Honolulu artesian areas. The basis of this suggestion was the concept that the Ghyben-Herzberg sector in each artesian area is a container whose content of water at any given time is indicated by the artesian head and whose capacity to supply water to wells is the difference between intake from rainfall and loss by leakage to the ocean, modified by gains from, or losses to, adjacent areas and by gains, or losses, in its own storage status.

The suggestion was set forth in detail in three letters to the Board of Water Supply (Hoyt, 1935). Various conferences were held discussing methods and objectives. As stated by Kunesh, one of the chief questions to which an answer was sought, was whether the artesian system of the Honolulu area could receive material aid by ground-water flow from adjacent areas if the heads in the Honolulu area were so lowered as to produce a hydraulic gradient toward the city (Kunesh, 1935). Another part of the doctrine of head lowering is that such lowering would also reduce the seaward leakage, and this would result in an increase of available water (Stearns, 1935). A more complete statement that we might make at this date is that lowering the head would tend to decrease flow to any areas of lower head, such as the ocean or adjacent ground-water areas, and would tend to increase flow to the Honolulu area from any areas of higher head, such as adjacent parts of Oahu. Further, as stated below, we must include under adjacent areas, the sub-sea-level part of the artesian structure. The net result of head lowering would be net gain to the basin in question whether by increase of inflow, or decrease of outflow, or some of each.[8]

As set forth in the Hoyt letters, each artesian area is subject to loss to the ocean and to each of the adjacent areas whose head is lower and also to gain of water from rainfall and from adjacent areas when their heads are higher. The rates of loss or gain according to head differences, the daily gain from rainfall under conditions of high, medium, or low rainfall, and the storage capacity of the aquifer per foot of head difference were unknowns to be determined by the solution of a series of equations after substituting the measured heads, known discharges, and other measurable parameters.

The number of terms in the whole series of equations was rather large, and in the conduct of the experiments efforts were made to hold heads, or discharges, constant for certain periods to simplify the calculations. Among the conditions to be determined was the nature of the flow of ground water in the aquifer. In doing this the several stations were tested at several different rates of pumpage, and drawdowns were measured. This procedure gave valuable information on a given station, itself, but it is now believed that the data were erroneously interpreted in regard to the problem of whether flow in the aquifer is prevailingly laminar or turbulent. This part of the mechanical test has been discussed in detail elsewhere (Wentworth, 1946), and it has been shown that flow in the aquifer is laminar, with rates proportional to the first power of the hydraulic gradient. Only in the very close vicinity of wells or pits do velocities become high enough to develop partial turbulent flow and, hence, in the formula $H = KQ^N$, a value of N greater than 1.00. While the determination of the value of N for the head-discharge relations in each station is of considerable practical value, it is now recognized that taking such a determination as applicable to the flow of water in the aquifer generally, remote from the wells, is unjustified. It was shown in the paper cited that the whole of the drawdown which is not linear and directly proportional to the discharge occurs in the rock within a very few feet of the well or sump and that the figures for drawdown in the aquifer are proportional to the discharge. Therefore, so far as the energy factor is concerned, the rates of flow, from one area to another or from the ground-water body to the ocean, may be assumed to vary with the first power of the head difference.

It was recognized in setting up the mechanical testing program that rainfall could not be controlled, and that to eliminate major difficulties through rainfall variation it was desirable to make the tests during periods of fairly consistent rainfall behavior. On the basis of later studies made by the writer it appears that the rate of addition of infiltrated rainfall to the main ground-water body is a complex and little-known function of the rain falling during several months previous to any date in question and most heavily influenced by rain 5 or 6 months earlier. It appears, therefore, that the attention to rainfall during the exact dates of the test was not closely relevant and that actual rates of addition of infiltrated rainfall might differ widely between two periods of similar contemporaneous rainfall.

When the various equations were carried through to solution, results were very unsatisfactory. For the main constants to be determined, values found were not even roughly consistent and in various instances were not of the same order of magnitude and in some cases were of the wrong sign. Considerable effort was made to refine measurements of head, where differences were often small, but no satisfactory solutions were reached.

Subsequent study has indicated that, apart from the imperfect values for rainfall increment and the misunderstanding in regard to the character of flow and the value of N, the most important source of error is that due to non-completed hydraulic flow and the consequent lag in

[8]The present writer participated in these discussions and the proposed plan was supported by him. The present conclusions and comments should not be taken as personal criticism of any of the persons involved, nor as indicating any dissatisfaction with the conduct of the tests. Points which now appear to have been overlooked and are probably the cause of failure to attain the main objectives were overlooked by the writer, equally with others, and in setting them forth now, he is drawing on knowledge of the system developed since 1934 and brought into focus by the tests themselves.

the achieving of equilibria conceived in the equations. In a small system of reservoirs and of large-diameter short pipes, while flow is not instantaneous, the transfer of water into and out of reservoirs might be practically complete after a few hours or days and measurements of stored quantities would be substantially correct, but this does not appear to be true in this system.

In recent years the concept of bottom storage and lag in the shrinkage of the lower part of the Ghyben-Herzberg lens has been elaborated (Wentworth, 1942). This is also discussed elsewhere in this report. It is sufficient here to point out that we now believe that if equilibria were reached in a few hours (no time at all was allowed in the original philosophy of the tests), the shrinkage of the top of the Ghyben-Herzberg lens by, say, 1 foot of head in 1 month, should be closely followed by a shrinkage of the bottom of the lens by about 40 feet. We know from practical experience that an excess of discharge over increment from rainfall of a few (5–10) million gallons daily will accomplish such a top shrinkage of 1 foot in 1 month, amounting to somewhat over 200 million gallons. On the other hand we know of no mechanism for disposing of the corresponding amount of 40 times 200 million gallons during 1 month. Neither do we have any ground for reducing the estimate of water involved in a 40-foot shrinkage sufficiently to resolve the discrepancy. It seems inescapable that changes in the position of the bottom of the Ghyben-Herzberg lens, because of the large amounts of water, must lag greatly behind the causal changes at the top. Similar lags must affect the movement of water from or to an adjacent area of different head. In fact, as we now believe, the head in a given area, while indicating roughly the amount of water above sea level, cannot be taken as a measure of the amount of water in the lens as a whole because we have no basis for assuming equilibrium to have been reached. A rate of rise or fall in the water table may indicate fairly closely a rate of increase or decrease in water stored just below the water table, but its validity as a measure is nearly nullified if lagging changes at the bottom due to earlier fluctuations are in progress, possibly at rates greater than, and even opposite in sign to, the indicated rates at the top.

Without further consideration of the theory of bottom storage at this point, it appears that we can no longer accept the postulate of Hoyt, that "when the head is the same at the beginning and end of a period, it is reasonable to assume that the amount of water stored underground is the same" (Board of Water Supply, 1935, p. 150). For now there is much evidence, particularly in the increasing salinities of certain wells, that despite the holding steady of the head at the top of the water table, there is a continuing shrinkage of the fresh water above the diffusion zone. This fact, while we still lack reliable measures of the amount of change in water stored, appears to constitute a fatal barrier to solution of the mechanical test problem along the original lines. Correspondingly, it appears as a quite adequate explanation of the discrepancies and reversed signs of various values resulting from direct solution of the equations.

If, and when, it is possible to utilize a more reliable measure of rates of gain from infiltration of rainfall, based on further refinement of those mentioned in another section, and when through direct measurement by test holes in the diffusion zone we can derive figures for the thickness of fresh water below sea level, a part of the procedure of the mechanical tests can be used as originally suggested. Meantime, the chief results have been with respect to operating procedure and with the transfer of pumping load from one station to another and are mostly not pertinent to this report.

ANALYSES OF HYDROLOGIC RELATIONS BY STATISTICAL METHODS

Following the mechanical testing of the several Honolulu isopiestic areas, as it became evident that this method would not yield significant results along the lines originally conceived, the writer attempted a different approach. Since the original testing involved various short periods and aimed at solution by ordinary algebraic methods, it appeared possible that use of statistical methods, so that all data through a given long period could be used, might yield definite results if the number of constants to be determined were small enough.

In setting up this procedure first reliance was on certain relationships which are a matter of common observation. First of these is that following rainy seasons the basal and artesian head rises, and after dry seasons the head falls. This condition holds even when the draft remains constant, though it is augmented when the increased rainfall results in a somewhat reduced draft and vice versa. We need to know the amount of rise corresponding to any given condition of increased rainfall, other things being equal.

We also know that when draft is increased during a period of fairly steady rainfall conditions, the head is reduced to some position below its former level where it will remain steady under the increased draft. It seems obvious that at the lower head there is less leakage to the ocean and to adjacent areas of lower head and more inflow from adjacent areas of higher head, the net gain being that demanded to make up the increase in draft. These approximate conditions have been known for a long time and were the basis of Hoyt's suggestion for mechanical testing.

However, following the inconclusive experience of the mechanical testing, certain changes were indicated. One of these is avoidance of short-term reliance on any assumption that the total amount in the ground-water body at any time is indicated directly by the head. This is replaced simply by the assumption that over a long period the net change in storage can be temporarily disregarded. Actually we believe that the amount in storage now at a given head is less than it formerly was. To the extent that this is true the difference represents an over-all error in the calculated amount of draft.

The other principal change is in the recognition that at any given time, or through any given period, the amount of water added through infiltration is dependent on the amount and distribution of rainfall through some period extending backward from the time or period in question.

Much of the work in these analyses has been in setting up and progressively trying various systematic rainfall indexes devised to represent the cumulation of past rainfall in some pattern to approximate the actual rate of infiltration. These various rainfall indexes will be discussed below.

The procedure used is that of multiple correlation to derive the coefficients A, B, and C in the equation: $D = A + Bf(R) - CH$, where D is the total measured draft, H is the head, and f(R) is some function of past rainfall used as the index of infiltration. In this equation it is assumed that there is a loss, represented by CH which is proportional to the first power of the head, and that there is a gain or loss proportional to the first power of the function of rainfall, in values which fluctuate on the positive or negative side of zero according to whether the rainfall cumulation has shown excess or deficiency. Therefore, the equation is a linear regression of draft on the values for head and for the function of rainfall, the equation as solved being the equation for a plane which satisfies the least squares condition.

Given the normal or average rainfall condition when the term Bf(R) becomes zero, the equation reduces to $D = A - CH$, which emphasizes the concept that from average rainfall there is infiltrated a fixed amount of water from which the draft is derived by subtracting the leakage, CH, proportional to head. This is an extremely simplified concept, but it is believed to include the two most important elements: that the total continuous increment to the Ghyben-Herzberg lens, when the latter remains constant, is divided between draft, water that is measured and accounted for, and water that is lost by various kinds of leakage which are at least roughly proportional to the head.

It is not necessary to detail the methods of multiple correlation which are set forth in various texts on statistics. There are several forms of procedure, but all are extensions of the process of finding a simple linear equation to fit a number of points in such fashion that the sum of the squares of the deviations of the actual Y from the computed Y is a minimum. This is in turn a logical extension of the calculation of the arithmetical mean of a number of observations, since the arithmetic mean is that representative value, from which the sum of the squares of deviations of individual readings is a minimum. Calculation by these methods, even in instances where the pattern of deviations may not precisely fit that of the so-called normal curve of error, or Gaussian distribution, is justified because it permits us to reach estimates of performance which can at any time be duplicated by ourselves or others and gives a basis for comparison of various assumptions and methods.

Before setting forth the several correlations that have been made along these lines, a single one, perhaps the most important, will be discussed for further clarification. This deals with the four Honolulu areas, 1 to 4 considered as a unit, and using average annual data for head, draft, and rainfall.

Since this particular series of f(R) shown in table 16 gave the best correlation and lowest probable error of any used for this period and scope, it will be useful to describe its derivation. Earlier assumptions in regard to the smoothing and lag of the rainfall effect on infiltration had shown that cumulation of each month's excess or deficiency of rain in relation to the mean gave values which increased too far in one direction, plus or minus. Trial was made of subtracting a percentage of the cumulative total each month, and it was found that such debiting at the rate of 3 per cent monthly gave the best result. By best result is understood that making up such a function by systematic calculation through the whole 180 months of the 15 years, calculating the average annual values and using these for f(R) in a new least squares solution for the equation ($D = A + Bf(R) - CH$), gave the lowest probable error of estimate of draft in a given series tested.

TABLE 16

TABLE OF DATA, HONOLULU SYSTEM (AREAS 1, 2, 3, 4)

YEAR	MEAN HEAD H	INFILTRATION f(R)*	MEAN TOTAL DRAFT D
	feet		*mgd*
1926	23.0	—157	38.4
1927	24.3	— 65	36.8
1928	27.7	+ 19	34.4
1929	26.2	—110	33.4
1930	27.8	— 71	31.2
1931	27.4	— 76	32.1
1932	29.4	+ 63	29.6
1933	28.8	+ 9	28.7
1934	26.6	—129	28.6
1935	27.4	— 72	29.5
1936	26.5	—108	30.8
1937	29.6	+ 59	29.7
1938	30.3	+ 99	31.1
1939	29.6	+138	30.3
1940	28.8	+ 21	32.8
Mean	27.56	— 25.3	31.83

* This f(R) is the so-called square-root-3-per-cent function.

However, it appeared that the effects of extremely high rainfall for a month would not be fully felt, nor likewise those of a single very dry month, even with the averaging achieved by the cumulation. Therefore, the device was used of taking as the monthly infiltration not the ratio of actual to mean rainfall but the square root of this ratio. Since ratios are on the plus or minus side of 1.00, the square roots of the ratios are reduced in their amplitude of variations above or below 1.00. (In the actual computation, for convenience, the whole is multiplied by 100 and on extracting the square roots these are again multiplied by 10 to keep the number series on the basis that average rainfall is considered as 100.)

The development of these numbers in deriving the f(R) from the rainfall data is shown in table 17.

This table shows the method of computing this particular f(R) from the original monthly rainfall indexes. A 2-year period for Area 3 has been used because it best illustrates the behavior of the values of f(R). Starting with a zero assumption, the heavy rainfall of the first 5 months of 1932 builds up fairly large positive values of f(R) which are not quite canceled by the low rainfall of the remainder of the year. However, the lesser build-up

TABLE 17

METHOD OF CALCULATING f(R)

MONTH	RAINFALL INDEX* (100 = Average)	SQUARE ROOT (× 10)	DIFFERENCE	CUMULATION	LESS 3% = f(R)
1932					
January	121	110	+ 10	+ 10	+ 10
February	397	199	+ 99	+109	+106
March	86	93	— 7	+ 99	+ 96
April	161	127	+ 27	+123	+119
May	115	107	+ 7	+126	+122
June	83	91	— 9	+113	+110
July	81	90	— 10	+100	+ 97
August	92	96	— 4	+ 93	+ 90
September	61	78	— 22	+ 68	+ 65
October	52	72	— 28	+ 37	+ 36
November	70	84	— 16	+ 20	+ 19
December	107	103	+ 3	+ 22	+ 21
1933					
January	147	121	+ 21	+ 42	+ 41
February	193	139	+ 39	+ 80	+ 78
March	121	110	+ 10	+ 88	+ 85
April	45	67	— 33	+ 52	+ 50
May	38	62	— 38	+ 12	+ 12
June	77	88	— 12	0	0
July	61	78	— 22	— 22	— 21
August	39	62	— 38	— 59	— 57
September	39	62	— 38	— 95	— 92
October	22	45	— 55	—147	—143
November	28	53	— 47	—190	—184
December	91	95	— 5	—189	—183

* Area No. 3, starting from zero.

of the first 3 months of 1933 is completely overbalanced by the markedly low rainfall of April to June, and the f(R) numbers are carried to nearly 200 in the negative direction during the latter part of 1933.

It is natural to ask, Why go to all this trouble? Why not just use the rainfall values themselves, or some moving average? Many of these have been tried and to date, in general, a function of the square-root, 3-per-cent-debit type yields lower probable errors and hence appears to be a more useful device.

Using an infiltration function built in this way, as shown in the preceding table and reduced to normal rain = 1.00, this equation was derived: $D = 98.6 + 3.39\ f(R) - 2.39\ H$.

This equation, from the data used, was found to give a probable error of 0.99 mgd in predicting the annual draft and was superior to that derived by use of any other f(R) for the same period and under the same conditions (fig. 22).

TABLE 18

ESTIMATED DRAFT, HONOLULU AREAS 1, 2, 3, 4.
$D = 98.6 + 3.39\ f(R) - 2.39\ H$

MEAN HEAD AREAS 1, 2, 3, 4	INFILTRATION High f(R) = +2.0	Medium f(R) = 0.0	Low f(R) = —2.0
feet			
28	38.46	31.68	24.90
25	45.63	38.85	32.07
22	52.80	46.02	39.24

It is desirable to point out what this equation can be used for and what it cannot do. We must also distinguish between its algebraic meaning and its hydrologic meaning. First of all, the equation is our most accurate means of estimating what draft we may expect during a year when rainfall has a certain condition and with a specified head, as shown in table 18.

The draft values shown in the table give the best estimate we have as to the effect of sustained dry weather or sustained wet weather on water available at a given head, as well as the effect of head in combination with various infiltration conditions. Since head is influenced by rainfall, it is not likely at present that we would have a head as high as 28 feet with an f(R) value as low as —2.0, nor a low head of 22 feet with a +2.0 value for f(R). Thus, in general, we would not expect a constant draft as great as 52.8 mgd without further lowering the head by drawing on storage, nor a draft as low as 24.90 mgd without concurrent rise in head. However, the remainder of the figures represent the general possibilities of Areas 1 to 4 combined, with the proviso that these figures are probably somewhat affected by yield from bottom storage, which may not be so great in the future.

In an algebraic sense there are certain indications of the equation which are suggestive without being taken as precise. For example, the coefficient C (2.39) is the amount in mgd by which the available draft increases as the head goes down 1 foot. It is approximately the rate of leakage per foot of head in the range represented by the data used. Owing to the interplay between the different terms of the equation, this cannot be taken as a precise measurement of the leakage factor.

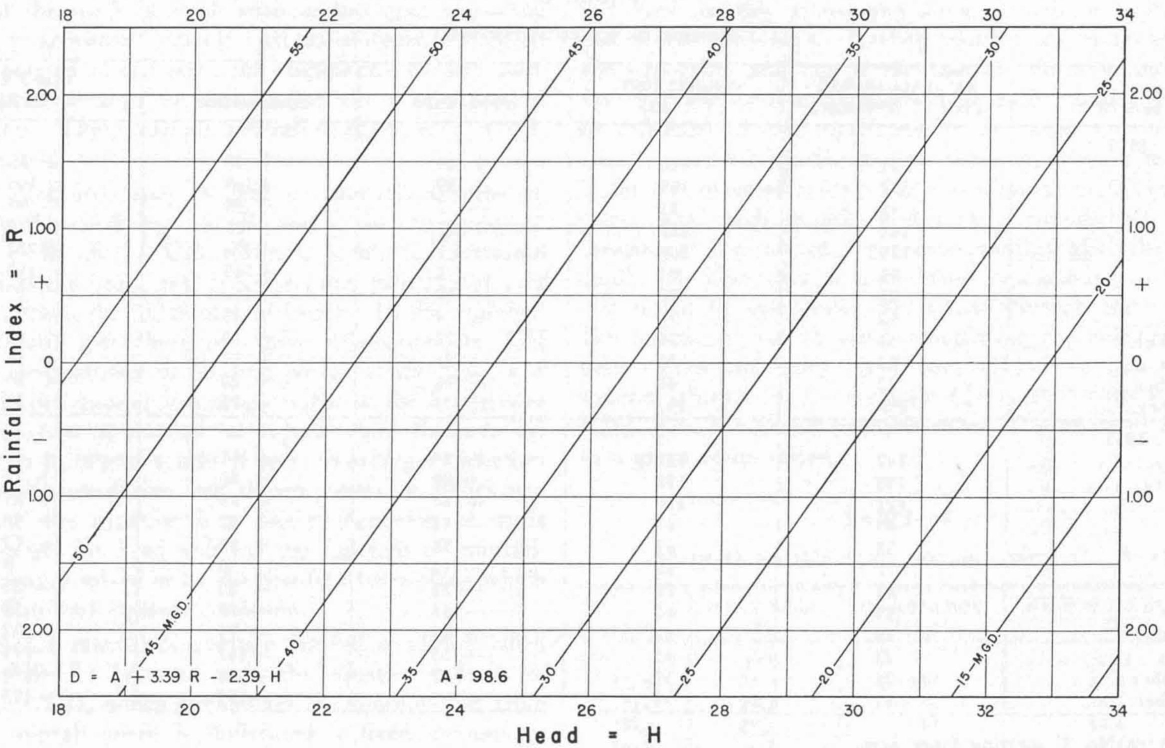

FIGURE 22. Diagram for head-draft-rainfall equation.

However, if we assume the leakage reduced to zero and assume the C term canceled, with infiltration term zero for normal weather conditions the equation reduces to D = 98.6.

This implies that the total infiltration may be of the order of 98.6 mgd, but the implication is subject to the weakness that the extrapolation is too great from the range of data used in solving the equation. The findings in this equation have been supported by those in some 20 other solutions in that the values for C in the three or four equations giving the lowest probable errors are about 2¼ to 2½ mgd per foot of head, and the values for A are in the range 90 to 100 mgd. These other equations will be discussed below.

It will be observed that the equation as set up has no term for draft from storage, that is, a term in which independent data are changes of head. Instead of complicating the equation by these data, the effect of this factor has been taken as a residual to be correlated against the head change during the month.

The procedure consisted of calculating from the equation the presumptive draft for each month and tabulating it alongside of the actual draft. In another column is shown the difference between the calculated draft and the actual draft, the difference being positive when the calculated draft is the greater and negative when the calculated draft is smaller. It is found that if the head changes are tabulated alongside the draft differences, with rising head as positive, there is a close parallelism in signs between the two (fig. 23). Thus, during a period of several months when the head is rising, the calculated draft is greater than the actual draft and vice versa. It is reasonably clear that when the actual draft shows a deficiency it is because the difference is applied to raising the water table. The device is then followed of dividing the excesses and deficiencies of water (column 4, table 19) by the head change in feet shown in column 5, recognizing that 1 mgd through an average month is 30.4 million gallons. The result of such division is that through the 15 years a quotient is obtained showing that 1 foot of rise or fall of the basal head in Area 1 to 4 accounts for 230 million gallons. Table 19 shows a sample segment of the tabulation.

Table 19 illustrates the method of calculation of the running ratio of excess or deficient draft to loss or gain of head. In order to compare similar signs in the table, the draft difference is considered positive when the computed draft is more than actual draft. It will be noted

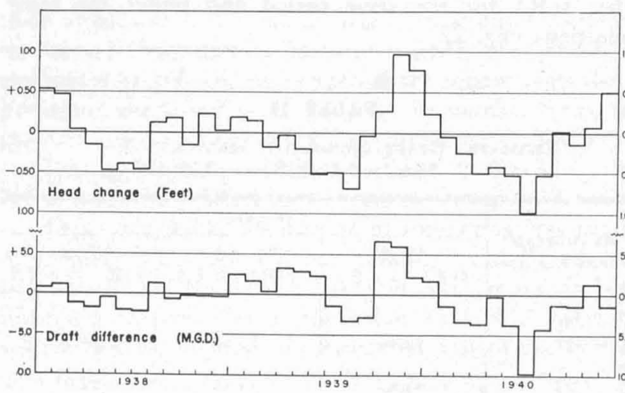

FIGURE 23. Segment of graph showing draft differences and head changes.

TABLE 19

DRAFT AND HEAD DIFFERENCES. AREAS 1–4, D = 98.6 — 3.39 f(R) — 2.39H

1	2	3	4	5
YEAR AND MONTH	ACTUAL DRAFT	COMPUTED DRAFT	DRAFT DIFFERENCE	ACTUAL HEAD CHANGE
1938	*mgd*	*mgd*	*mgd*	*feet*
January	27.04	27.8	+0.76	+0.53
February	26.03	27.1	+1.07	+0.47
March	28.76	27.7	—1.06	+0.04
April	29.83	28.2	—1.62	—0.15
May	30.47	30.0	—0.47	—0.46
June	32.68	30.8	—1.88	—0.38
July	33.82	31.8	—2.02	—0.45
August	30.54	32.0	+1.46	+0.13
September	31.05	30.5	—0.55	+0.19
October	30.64	30.6	—0.04	—0.15
November	29.53	29.4	—0.13	+0.23
December	29.32	29.5	—0.18	+0.02
			+3.47 —7.78	+1.61 —1.59
1939				
January	26.90	29.4	+2.50	+0.20
February	27.62	29.3	+1.68	+0.16
March	29.48	29.9	+0.42	—0.16
April	28.06	31.3	+3.24	—0.03
May	29.10	32.0	+2.90	—0.19
June	31.24	33.7	+2.46	—0.50
July	35.75	34.4	—1.35	—0.48
August	35.80	35.3	—3.20	+0.69
September	31.77	34.6	—2.83	—0.03
October	28.92	35.6	+6.68	+0.28
November	27.69	33.7	+6.01	+0.98
December	28.15	30.4	+2.25	+0.79
			+28.14 —7.38	+2.41 —2.08
1940				
January	27.52	29.2	+1.68	+0.25
February	29.63	28.3	—1.33	—0 04
March	30.90	27.5	—3.40	—0.24
April	31.75	28.2	—3.55	—0.49
May	30.03	29.8	—0.23	—0.40
June	34.00	30.3	—3.70	—0.51
July	31.87	32.0	—9.87	—0.98
August	38.18	34.0	—4.18	—0.52
September	34.35	33.2	—1.15	+0.04
October	33.96	32.6	—1.36	—0.13
November	30.78	32.1	+1.32	+0.09
December	30.92	29.5	—1.42	+0.52
			+ 3.00 —30.19	+0.90 —3.31
			+34.61 —45.35	+4.92 —6.98

For head rise (34.61 ÷ 4.92) 30.4 = 213.8 mg
For head fall (45.35 ÷ 6.98) 30.4 = 198.4 mg

that in a broad way the signs correspond between draft difference and head change, with some individual discrepancies. Within the 3 years shown, the quotient or rate for head rise is 214 million gallons, while that for head loss is 198 million gallons. For the entire period, 1926 to 1941, the head rise rate is 203 million gallons and the head loss rate, 257 million gallons. The general changes in these rates are shown in the following tabulation:

PERIOD	HEAD RISE RATE	HEAD LOSS RATE
1926–29	189	310
1930–33	210	259
1934–37	255	119
1938–41	158	340
1926–41	203	257

It is clear enough that other factors than contemporary head change are involved. In brief, it appears that during the earlier period some consistent gain was felt which was additive during head-loss periods and subtractive during head-gain periods but that this condition was reversed during the 1934–1937 period and resumed during the 1938–1941 period. It is difficult to avoid the view that this changing net relationship between the residuals for head gain and head loss is due to lagging gain or loss from the bottom storage or from adjacent areas of changing heads, but adequate examination of such a hypothesis has not yet been accomplished.

However, it seems fairly well indicated that over the period in question, including an average amount of error from other causes, the capacity of 1-foot head difference approximates 230 million gallons. Because of the fact that there is included in this calculation just about as much head rise as head fall and that the errors due to yield from external sources are partly canceled out in the long run, we come to the view that this is an important hydrologic measure for the Honolulu area.

It will be impossible in this section to present a complete discussion of the various analyses of hydrologic relationships that have been made. Many of these are exploratory or incomplete, but, at the same time, they represent an important body of preliminary studies and will form a basis for more complete and definitive studies at a later date.

An attempt is made in table 20 to tabulate the various multiple correlations that have been made and to give the most important data defining the tests.

TABLE 20

Equations and Rainfall Functions

BY YEARS — AREAS 1–4, COMBINED — YEARS 1926–1940

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
(1)	1.30	D = 63.4 + 1.75 f(R) — 1.14 H	3-month moving average, preceding 3 months
(2)	1.30	D = 61.8 + 0.316 f(R) — 1.09 H	3-month moving average, current and preceding 2 months
(3)	1.27	D = 64.9 + 2.59 f(R) — 1.20 H	6-month moving average, current and 5 preceding months
(4)	1.28	D = 64.1 + 2.21 f(R) — 1.17 H	Moving average of the current month, twice each of the preceding 3 months and once each of the fourth and fifth months back.
(5)	1.22	D = 65.6 + 0.368 f(R) — 1.36 H	Cumulation of excesses and deficiencies, debited 4% each month
(6)	1.16	D = 114 + 2.20 f(R) — 2.94 H	Cumulation same, debited 3% each month
(7)	1.19	D = 113 + 2.01 f(R) — 2.91 H	Cumulation same, debited 2% each month
(8)	1.18	D = 114 + 1.98 f(R) — 2.90 H	Cumulation same, debited 1% each month
(9)	0.99	D = 98.6 + 3.39 f(R) — 2.39 H	Square root of monthly ratio, excesses and deficiencies cumulated and debited 3% each month
(10)	1.28	D = 110 + 4.90 f(R) — 2.77 H	Root 2.2 of monthly ratios, cumulated, debited 3% each month
(11)	1.31	D = 102 + 3.32 f(R) — 2.49 H	Root 1.8 of monthly ratios, cumulated, debited 3% each month
(12)	1.29	D = 59.3 + 0.243 f(R) — 1.00 H	Monthly rainfall index, no treatment
(13)	1.25	D = 68.6 + 2.93 f(R) — 1.33 H	5-month moving average of 5-month moving average
(14)	0.90	D = 103 + 3.80 f(R) — 2.51 H	Square root, 3% debit based on different mean and starting point from No. 9, above

BY YEARS — AREAS 1–4, COMBINED — YEARS 1936–1942

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
(15)	1.07	D = 24.6 — 2.09 f(R) + 0.255 H	See (9)
(16)	1.11	D = 41.3 — 1.23 f(R) — 0.344 H	See (14)

BY MONTHS

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
(17)	2.52	D = 88.7 + 0.84 f(R) — 1.96 H	See (9)

* In course of calculation, the rainfall ratios have been handled on the basis that normal rainfal equals 100; in solving equation, these are on the basis that normal equals 1.00.

TABLE 20—*Continued*

BY YEARS — AREAS 1-4, SEPARATE — YEARS 1930–1941

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
Area 1 (18)	0.48	D = 10.8 — 0.095 f(R) — 0.176 H	Same as (9) computed for 1–4
Area 2 (19)	0.51	D = 46.3 + 1.43 f(R) — 1.20 H	Same as (9) computed for 1–4
Area 3 (20)	0.46	D = 28.2 + 0.66 f(R) — 0.66 H	Same as (9) computed for 1–4
Area 4 (21)	0.65	D = 26.4 + 0.97 f(R) — 0.76 H	Same as (9) computed for 1–4
Area 1 (22)	0.48	D = 15.6 + 0.25 f(R) — 0.35 H	Square root, 3%, computed for Area 1
Area 2 (23)	0.54	D = 37.7 + 1.01 f(R) — 0.89 H	Same, computed for Area 2
Area 3 (24)	0.38	D = 33.0 + 0.95 f(R) — 0.79 H	Same, computed for Area 3
Area 4 (25)	0.52	D = 29.7 + 1.09 f(R) — 0.85 H	Same, computed for Area 4

BY MONTHS — AREAS 1-4, SEPARATE — YEARS 1939–1944

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
Area 1 (26)		D = 29.6 + 0.73 f(R) — 0.82 H	Same as (22) for Area 1
Area 2 (27)		D = 27.0 + 0.75 f(R) — 0.52 H	Same as (23) for Area 2
Area 3 (28)		D = 26.3 + 0.67 f(R) — 0.60 H	Same as (24) for Area 3
Area 4 (29)		D = 84.2 + 0.92 f(R) — 2.82 H	Same as (25) for Area 4

AREA 1 — YEARS 1936–1946

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
By Months (30)	1.09	D = 39.9 + 1.51 f(R) — 1.20 H	Same as (22) computed for Area 1
(31)	1.19	D = 17.4 + 0.28 f(R) — 0.42 H	5-month moving average
(32)		D = 19.0 + 1.48 f(R) — 0.48 H	5-month moving average of 5-month moving average
By Years (33)	0.80	D = 10.7 + 0.13 f(R) — 0.15 H	Same as (22) computed for Area 1
(34)	0.83	D = 7.3 + 2.02 f(R) — 0.033 H	Same as (31)
(35)		D = 7.8 + 1.42 f(R) — 0.051 H	Same as (32)

AREA 1 — YEARS 1938–1944

	Probable Error (mgd)	Equation A B C	Rainfall Function* f(R)
By Months (36)	0.63	D = 44.3 + 1.51 f(R) — 1.35 H	Square root, 3% debit
By 3-month period (37)	0.55	D = 30.0 + 0.33 f(R) — 0.84 H	Square root, 3% debit
By 6-month period (38)	0.43	D = 29.1 + 0.28 f(R) — 0.81 H	Square root, 3% debit
By Years (39)	0.48	D = 26.3 + 0.21 f(R) — 0.71 H	Square root, 3% debit

* See footnote, page 86.

TABLE 20—*Continued*

	Probable Error (mgd)	Equation A	B	C	Rainfall Function* f(R)
BY YEARS — AREAS 1-3 YEARS 1936–1942					
(40)	0.25	D = 3.5	— 0.76 f(R)	+ 0.097 H	Square root, 3% debit
(41)	0.29	D = 24	+ 0.41 f(R)	— 0.46 H	Square root, 3% debit
(42)	0.89	D = 23	+ 0.62 f(R)	— 0.49 H	Square root, 3% debit
AREA 4—YEARS 1930–1941					
(43)	0.38	D = 28.1	+ 1.06 f(R)	— 0.78 H	Same as (25) computed for 4
(44)	2.94	D = 134	+ 3.3 f(R)	— 4.55 H	Same as (43)
AREA 6, PEARL HARBOR — YEARS 1925–1940					
(45)	7.47	D = 431	+ 0.139 f(R)	— 12.0 H	Square root, 3%

* See footnote, page 86.

TABLE 21

ANNUAL RAINFALL FUNCTIONS

YEAR	EQUATION NUMBER: 1	2	3	4	5	6	7	8	15,17, 18,19, 20,21, 40,41, 42,9	10	11	12
	Moving average of excess or deficiency, 3 previous months	Moving average, current and 2 previous months	Moving average, previous 6 months	Combination of equations 2 and 3, this table	Cumulation, starting with 1,000, debited 4% each month	Same, debited 3% each month	Same, debited 2% each month	Same, debited 1% each month	3% debit, using square root of rainfall ratio	3% debit, using 2.2 root of rainfall ratio	3% debit, using 1.8 root of rainfall ratio	Excesses and deficiencies of actual rainfall
1925	—15.4	—17.1	—13.3	—14.3	921	916	918	908	+ 95			
1926	—37.6	—38.9	—39.3	—38.5	610	581	549	511	—157	—163	—204	—0.40
1927	+31.0	+37.3	+28.1	+29.6	873	816	752	679	— 65	— 81	— 92	—0.55
1928	+ 8.4	— 2.0	+ 0.8	+ 4.6	1,089	1,056	1,010	932	+ 19	— 3	+ 18	—0.17
1929	—19.0	—14.7	—17.2	—18.1	867	838	796	716	—110	— 80	— 86	—0.13
1930	+17.1	+15.7	+11.7	+14.4	948	914	865	773	— 71	— 51	— 53	+0.08
1931	— 3.3	— 5.1	— 4.0	— 3.6	921	889	841	764	— 76	— 57	— 64	—0.06
1932	+19.0	+16.7	+25.4	+22.2	1,204	1,194	1,165	1,078	+ 63	+ 47	+ 65	+0.17
1933	—16.6	—19.0	—15.2	—15.9	1,055	1,064	1,057	997	+ 9	— 0	+ 9	—0.20
1934	—13.9	— 9.6	—21.7	—17.8	808	801	780	712	—129	— 95	—110	—0.06
1935	— 0.9	— 2.8	+ 1.3	+ 0.2	912	896	964	787	— 72	— 60	— 67	—0.06
1936	— 4.2	+ 2.1	—11.7	— 8.0	822	793	745	647	—108	— 95	—108	+0.09
1937	+19.3	+16.0	+26.1	+22.7	1,138	1,117	1,079	987	+ 59	+ 37	+ 45	+0.16
1938	+10.7	+ 8.4	+11.8	+11.2	1,162	1,166	1,152	1,084	+ 99	+ 60	+ 69	+0.04
1939	+14.6	+18.2	+ 8.8	+11.7	1,201	1,221	1,233	1,192	+138	+ 81	+ 97	+0.17
1940	+22.2	—28.5	—14.6	—18.4	994	1,019	1,045	1,027	+ 21	+ 4	+ 3	—0.30
1941									—146	—106	—134	
1942									—125			

TABLE 21—*Continued*

YEAR	EQUATION NUMBER							
	13	14, 16	22, 26 30, 33 36, 37 38, 39	23, 27	24, 28	25, 29 43, 44	34, 31	32, 35
	5-month moving average of 5-month moving average of rainfall	Square root debited 3% monthly, based on different mean and starting point from Equation 9	Square root, debited 3% monthly, computed for Area 1	Square root, debited 3% monthly, computed for Area 2	Square root, debited 3% monthly, computed for Area 3	Square root, debited 3% monthly, computed for Area 4	5-month moving average of rainfall, Area 1	5-month moving average of 5-month moving average of rainfall, Area 1
1925								
1926	— 40	—177						
1927	+ 17	— 88						
1928	+ 15	— 4						
1929	— 23	—113						
1930	+ 7	— 75	—101	—109	—128	—173		
1931	— 2	— 90	—136	—137	—132	—188		
1932	+ 31	+ 45	+ 2	+ 12	— 8	— 58		
1933	— 11	— 15	— 70	— 46	— 91	—125		
1934	— 23	—156	—174	—180	—241	—242		
1935	+ 3	—102	—139	—156	—181	—191		
1936	— 13	—140	—157	—190	—219	—196	+0.024	—0.052
1937	+ 55	+ 29	— 1	— 27	— 55	— 18	+0.24	+0.28
1938	+ 51	+ 72	+ 67	+ 18	+ 5	+ 38	+0.21	+0.21
1939	+ 9	+107	+ 82	+ 63	+ 56	+ 85	+0.10	+0.083
1940	— 25	— 4	— 6	+ 1	— 17	— 10	—0.118	—0.073
1941		—176	—169	—151	—177	—186	—0.265	—0.282
1942			—171	—174	— 98	—207	+0.026	+0.014
1943			—102	— 76	— 62	—122	+0.027	+0.085
1944			—232	—148	—226	—330	—0.26	—0.27
1945				—334			—0.36	—0.34
1946				—571			—0.21	—0.25
1947				—540				

Certain general comments on the behavior of coefficients in such equations are desirable. First of all, given the values of the two independent variables, the solution under the least squares procedure determines the values of A, B, and C such that, taken in the equation, the sum of the squares of the deviations are at a minimum. In general, if the pattern of variations in a given independent variable has high correlation with the pattern for the dependent variable, the coefficient of that variable will take such value as to make the fullest beneficial use of the fluctuations in the independent variable. If the pattern is of high correlation, the absolute value of the variations (standard deviation) is unimportant and the coefficient will be determined such that the standard deviation of the term (coefficient times the variable) gives the optimum effect. The absolute values of B are somewhat variable since the absolute range of variation in the different series of f(R) is quite variable.

On the other hand, when the pattern of variation of an independent variable corresponds very little with the pattern of the dependent variable to be explained, the coefficient grows smaller; if the independent variation is wholly irrelevent, the coefficient becomes zero, or if it is reciprocal or in reverse the sign of the coefficient changes.

Since the series f(R) has both negative and positive values and is at zero for normal or average rainfall, the term is eliminated in total effect and we have D = A — CH, in which case it is evident that the coefficients A and C will be so adjusted that, on the average, A — CH will be equal to the real value of D (draft). This relationship in shown in the straight line represented by the equation when the term Bf(R) is omitted.

However, the term Bf(R) has its effect in the degree to which the pattern of variations of f(R) is highly correlated and the coefficient B becomes progressively larger and more effective. Moreover, if of two independent variables used to explain a third dependent variable, both have significant correlation of opposite effect in the equation, the coefficients of both may grow larger to reach that point where the algebraic sum, on the average, gives the best correlated effect on the dependent variable.

Or the constant of the term A may be forced up or down, according as there is strong reciprocal correlation in the value of C or a net residue in the average value of the term Bf(R) increased by increase in the value of B.

This discussion shows why the values of A, B, C are not fixed independently but vary each according to the composite behavior of all and the values of the independent variables. It is quite apparent that rainfall and head are not truly independent but are physically related. Under these conditions, the values of f(R) may in some of the series develop so high a correlation that their maximum benefit is achieved by a high value of B, the effect then brought back to suitable average value by increased values of C in the negative term —CH.

On the other hand, the correlation of the term f(R) may fall so low or even become reversed so that the dominant correlative effect is left in the low values of the term —CH with a low value of C. Indeed this process can go so far as to reverse the sign of CH to positive. Until we have independent knowledge of the values of C or A, we can only be guided by the values of the probable error of prediction (see preceding table, also figure 24). In figure 24 the values of A and C have been plotted to show their direct linear relationship. Values of the PE have also been plotted against the values of C. Distribution of these shows a minimum in the neighborhood of C = 2 to 2.5, which corresponds to A = 90 to 100.

The data presented above represent several different empirical patterns of the infiltration function. Since the rainfall distribution in time and in space may be regarded

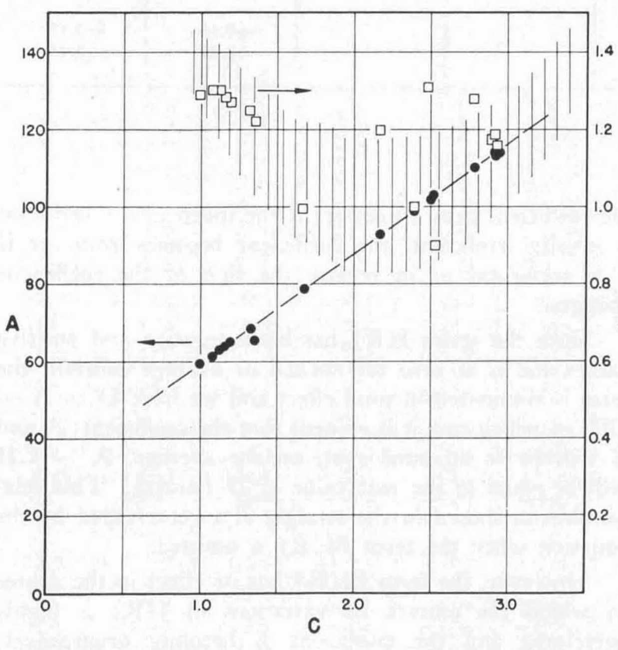

FIGURE 24. Graph showing reciprocal relations of coefficients and corresponding probable errors of prediction. As noted in the test, the values of A and C necessarily become reciprocally adjusted to one another by solution of the equation, giving rise to a straight line (dots). The lowest values of the probable errors of estimate have been obtained in the range 2.0 to 2.5 mgd for C and the range 90 to 100 mgd for A, leading to the indication that the true values are here approximated.

as having almost infinite variety, it is not to be hoped that data from a small number of gages will, with any kind of mathematical manipulation, eliminate a residue of unresolved variation. The present stage is shown by the value of the residuals. For the Honolulu areas the probable error of predictions, based wholly on the annual means without reference to head or rainfall, for the period 1926–1940 was 1.89 mgd. By taking account of head alone and solving an equation in the form $D = A - CH$ ($D = 61.06 - 1.061\ H$), the probable error is 1.27 mgd.

Finally, using the best series of f(R) yet worked out (Equation 14), we reach the probable error of 0.90 mgd, which is slightly under half the original value. It is probable, though the test has not been completed, that by making a correction for head changes during the year, the probable error of prediction can be carried down to less than a third of its original value. Further improvement may be achieved when additional correlations are attempted to throw light on the effect of bottom storage lag and on lagging transfers between adjacent areas. Data are presently sufficient to attempt such calculations when time and competent personnel are available, but longer periods of adequate data will be required to yield the most reliable values for some of the critical parameters.

In table 22 an attempt has been made to compile the approximate values of certain quantities and dimensions of the system, with notes on the conditions and bases of the calculations.

TABLE 22

HYDROLOGIC VALUES BASED ON CORRELATION EQUATIONS

Inflow to basal body from infiltration, including adjustment with adjacent areas and bottom storage, plus or minus. Based on A values in equations showing minimum errors:

Honolulu Areas 1 to 4, combined	90–100 mgd
Area 1	10–16 mgd
Area 2	38–46 mgd
Area 3	28–33 mgd
Area 4	26–30 mgd

Coefficient of ocean leakage, in relation to first power of head, applying to range from 20 to 33 feet. Based on determined coefficient C, in equations showing minimum errors:

Honolulu Areas 1 to 4, combined	2.4 to 2.5 mgd per foot of head
Area 1	0.18–0.35 mgd/ft.
Area 2	0.9 –1.20 mgd/ft.
Area 3	0.66–0.79 mgd/ft.
Area 4	0.76–0.85 mgd/ft.

The data offered in table 23 should be regarded as approximate only, and they are offered only by way of indicating the direction of results which can probably be attained when this line of attack can be carried to more advanced stages, using more complete and longer records, and following certain lines which can now only be suggested.

THE GHYBEN-HERZBERG PRINCIPLE

The condition of flotation of fresh water on salt, within the permeable rocks of an island in the ocean, is commonly referred to as the Ghyben-Herzberg theory.

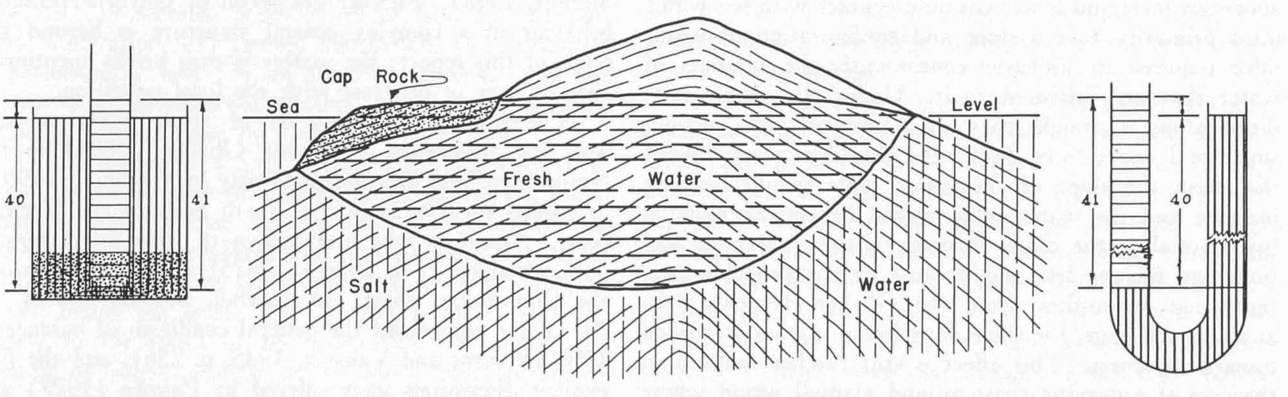

FIGURE 25. Diagram showing Ghyben-Herzberg balance in three forms. In the center is the ideal section of a small permeable island with a less permeable caprock fringe on one side. On the right is a U-tube with a higher column (horizontal hatching) of fresh water on one side balanced against a lower column of salt water (vertical hatching) on the other. On the left the same condition is shown with the higher column of fresh water in a small tube with the lower column of salt water in a larger vessel surrounding the tube. In all these cases the fresh-water column is shown with an exaggerated excess of height over the salt-water column; the real ratio is about 41:40, corresponding to the 40:41 ratio of the density of fresh to salt water.

At this date it is more appropriate to call it a principle. It is a long established fact in physics that any body which floats in a liquid will take a position so that a volume of the liquid equal in weight to the floating body is displaced and the remainder of the floating body will emerge above the level of the liquid. So if a floating body has a specific gravity of only 0.9, then only 0.9 of its volume need be submerged in water of specific gravity of 1.0 to support its weight, and the remaining one tenth of its total volume, or one tenth of its height if its cross section be uniform, will rise above the level of the water. This is no theory; it is a fact.

TABLE 23

CALCULATED YIELDS FOR AVERAGE RAINFALL AND AVERAGE AND LOW HEADS FOR AREAS 1 TO 4, AND THE FOUR AREAS TOGETHER (PERIOD 1930–1941)

	AVERAGE HEAD		LOW HEAD	
	Head	Yield	Head	Yield
	feet	*mgd*	*feet*	*mgd*
Area 1	26.5	6.14	21.5	7.02
Area 2	29.9	10.42	22.3	19.54
Area 3	29.4	8.66	21.7	13.88
Area 4	27.0	5.88	19.7	11.43
Areas 1–4	28.2	31.20	21.3	47.69

Storage coefficient, in million gallons per foot of head at the water table. Based on dividing differences between calculated draft and actual draft by changes in head during each month.

Honolulu Areas 1 to 4, combined	230 mg
Area 1	65 mg
Area 2	78 mg
Area 3	90 mg
Area 4	71 mg
Total	304 mg

The chief essential for this condition in the case of water in the rocks of an island is that the flow of water must be sufficiently retarded so that the fresh-water mass acts somewhat as a fixed mass and does not immediately mingle with salt water as it would in the open ocean. In some places this is the case, and it is found by direct test that given a body of ground water 1 or 2 or 3 feet above the average sea level along a coast, there is also a portion of the fresh-water body which extends to 40 or 80 or 120 feet below sea level. This follows the same flotation equation, so that 41 volumes of fresh water of specific gravity 40 has the same weight and balances 40 volumes of salt water of specific gravity 41. Thus the mass of fresh water moves downward until 40/41 of its volume has displaced the 40 volumes of the sea water which equal its entire weight and is left with 1/41 of its volume above sea level in a manner like any other floating body.

The operation of this principle can easily be shown by placing fresh water inside a glass tube which stands in a cylinder containing salt water or any other slightly heavier liquid. To retard the diffusion and mixing of the two liquids, sand can be placed in the lower parts of the two tubes (see fig. 25). If the specific gravities of the two liquids are in the ratio $\frac{n+1}{n}$, then the surface of the lighter liquid will stand above that of the heavier by about 1/n of the depth to the zone of contact between the two. If fresh water is added to or subtracted from the fresh-water column, its level will move so as to restore the pre-existing difference of level, and the same holds true of the outer column of salt water or other heavy liquid except that because of its smaller area the adjustment will be much more prompt in the small tube than in the large. In nature, where the level of the salt-water column is mean sea level, this condition for any moderate period is fixed except for the rapid, symmetrical fluctuations due to tides.

Given such a fixed level of the heavier salt water, we have a pressure gradient downward from sea level based on the density of sea water which at any one position of contact with a fresh-water column must be balanced by a height of fresh water rising to above sea level in order to hold the boundary in a fixed position. The fresh ground water along any coast where it stands above sea level and is in hydraulic contact with sea water must primarily have a slope and configuration of water table required to discharge continuously the amounts of water that are delivered to it. Under the simple condition along a straight coast of a uniform cross section, since total water to be discharged would increase toward the coast, the slope of the water table would likewise increase and the water table would be convex along a line normal to the coast. Moreover, since the cross section may become less and because of the probable concentration of outflow from the Ghyben-Herzberg lens at its coastal edge, the slope is probably further steepened toward the coast. This effect is still further induced in the case of a curving coast around a small island where the area of rainfall infiltration is proportional to the second power of the radius or the perimeter through which the water must escape. Thus it is clear that the upper surface of the accumulated ground water will be convex.

Now if such a configuration of surcharge over the level of the ocean is maintained, the contact between fresh water and salt water will be pressed downward until, on the average, the fresh-water column has the same weight as the salt-water column of lesser height. Given a convex upper surface, the induced lower limit for equilibrium is a much more deeply convex surface with its form somewhat generalized because the pressure effects are transmitted in all directions rather than vertically only. However, the form in a somewhat homogeneous, circular island would be closely that of a very unsymmetrical, double convex lens, with thickness of the sub-sea-level portion nearly 40 times that of the part above sea level.

So far as we have knowledge of the Honolulu–Pearl Harbor aquifer, it appears that the lower part of the Ghyben-Herzberg lens is developed to its full geometrical form, unconstrained by layers or masses of rock of materially less permeability than the mass as a whole. Much the more common condition along other coasts of the world is that where the rock structure is not homogeneous to sufficiently great depths to favor the formation of a symmetrical lens. Where various strata or masses of contrasting permeability pass from the fresh-water zone to the salt-water zone, the avenues of greater permeability respond to existing pressure contrasts, each according to its own contemporary fresh-water level, and there result various contrasted positions of the zone of transition between fresh and salt water and degrees of invasion of salt water. In such places it is possible for saline invasion to be taking place in one aquifer and in relation to wells drilled to one depth while the reverse condition may exist in another aquifer above or below the first one. The possibility of such conditions is augmented when there exist between the several aquifers other layers of rock which are less permeable than any of these aquifers and which inhibit merging by cross flow.

The demonstration and adequate outlining of such conditions, which are in accord with the Ghyben-Herzberg principle, require extensive drilling and other measurements of hydraulic status, such as have been carried out notably in Holland and in the Los Angeles area of California (Krul and Liefrinck, 1946; Poland, Garrett, and Sinnott, 1948). Further discussion of Ghyben-Herzberg behavior in a complex coastal structure is beyond the scope of this report; the matter is thus briefly mentioned here by way of contrast with the local condition.

The principle of flotation of fresh water on salt was first recognized by Badon Ghyben (1889) in the Netherlands and also independently by Herzberg (1901) in studies on islands in the North Sea, off the German coast. Attention was first drawn to it in an American publication by J. S. Brown (1925) in his studies along the Connecticut coast. In Hawaii, W. D. and A. C. Alexander recognized the general condition of balance in 1908 (Stearns and Vaksvik, 1935, p. 256), and the first explicit discussions were offered by Palmer (1927) and McCombs (1927). Drilling on Oahu of several hundred wells which penetrate the Ghyben-Herzberg lens under artesian conditions, has permitted extensive compilation of data bearing on the principle.

The elementary fact of fresh water extending below sea level by an amount approximating 40 times the head of fresh water above sea level is a matter of common experience in a great many wells that have been drilled to depths of 900 to 1,000 feet. The fact that the boundary between fresh and salt water is not a sharp one, as well as the lagging deviation from true balance, prevent a precise determination of the ratio. A series of samples of sea water from various places around and between the islands of Hawaii gave, at the same temperature, a specific gravity ratio against fresh water of 1.0261, which corresponds to the ratio 38.3:1 as the most probable figure. For general discussion it is most convenient to refer to 40:1 (Wentworth, 1939b).

It has been observed in a great many wells that water somewhat more saline than infiltrated rain water is often yielded by wells whose uncased bottom portion is within 1 or 2 hundred feet of the theoretical boundary between fresh water and salt, and it has been stated that "depth of the zone of diffusion may be considerable—as much as 100 to 300 feet." (Chaffee, 1929.) It is more and more apparent that there can be no single figure for the thickness of this zone, and from the variability of depths at which saline encroachment takes place we are forced to conclude that the boundary must take the form of extremely irregular interpenetration of fresh into salt and salt into fresh water by streamers of water of one quality drawn by hydraulic conditions into the realm of the other. The average effect of such irregular interpenetration must be a transition thickness of several hundred feet in most places but with great variation in the way in which individual wells cut the irregular transition zone, as well as increasing deviations due to more drastic withdrawal from wells and general lowering of the basal head. Measurement of the thickness at any one place and time could possibly be accomplished through a multiple-pipe test well, as proposed elsewhere, but any such figure would be valid only for those conditions, and an enormous amount of sampling and measurement is needed before any empirical summary can be made.

The writer has elsewhere set forth certain of the factors which seem to control the formation and growth of a Ghyben-Herzberg lens. The essential conditions are listed as (1) suitable permeability of aquifer, (2) adequate infiltration, (3) limited fluctuation, (4) regularity of permeability, and (5) an effective caprock. The last of these is not absolute but is found with the more extreme instances such as those on Oahu.

In the course of a brief study of ground-water conditions on the 3-square-mile island of Angaur in the Palau group, it appears that deterioration of the quality of water in the Ghyben-Herzberg lens has been the result of dragline mining of phosphate rock in the zone just at and below sea level. This change is apparently due largely to the effect of the excavation in causing the merging of larger openings at the water table and below and in providing greater storage of water in areas near the coast at the water-table level (Wentworth, Mason, and Davis, in press).

While the principle of the flotation of fresh water on salt with the formation of the Ghyben-Herzberg lens has been somewhat common knowledge in Hawaii for the past three decades, one aspect of that condition, that of volume changes and storage, has only more recently been recognized and set forth in outline (Wentworth, 1942, 1949). The ratio of 40 to 1 between the thickness and volume of the portion of the Ghyben-Herzberg lens below sea level and that above sea level focuses attention on the portion below sea level as a reservoir, and this has been designated as "bottom storage" in contrast to the "top storage" which lies above sea level. The relationships and behavior of these two parts of the lens are discussed in the section which follows.

THE CONCEPT OF BOTTOM STORAGE

The condition of bottom storage is a natural consequence of the Ghyben-Herzberg principle of hydrostatic balance between fresh and salt water in the permeable rocks of an oceanic island. According to this theory, as has been stated, the fresh water of the main ground-water body floats on sea water with 1 part above sea level and 40 parts below (Brown, 1925; Palmer, 1927; Stearns and Vaksvik, 1935). Thus for each foot of fresh water above sea level, there are 40 feet of fresh water below sea level. The ratio 40:1 is based on sea water having a specific gravity of 1.025, about 1/40 heavier than fresh water. According to extensive measurements near Honolulu, the true figure here is probably about 1.026 and the ratio nearer to 38.3. For simplicity we use the round number 40. If this condition exists, and if the water table changes by 1 foot, up or down, a new equilibrium will be reached only when the lower limit of fresh water has changed by 40 feet in a reverse direction, down or up, correspondingly. The two parts of the fresh-water body, above and below sea level, which are thus in balance at a 1:40 ratio, have been called top and bottom storage (Wentworth, 1942).

It follows from the Ghyben-Herzberg principle that when the thicknesses of top and bottom storage are not in the ratio required for equilibrium, water will tend to move toward the deficient part. Direct and rapid gains or losses of water due to fluctuations in rainfall or draft take place primarily in top storage by rise or fall of the water table. Slower, secondary changes in bottom storage take place in response to the levels maintained in top storage.

There is probably a large and fairly steady loss from bottom storage directly to the ocean at and near the seaward edge of the caprock. This is part of the equilibrium between rainfall and discharge and does not bring about changes in volume of bottom storage. Marked changes in volume of bottom storage, plus or minus, can come about only in response to changes in Ghyben-Herzberg equilibrium due to change in top storage by rise or fall of the water table. Bottom storage can gain fresh water only by transfer from top storage; losses from bottom storage induced by lowering of the water table take place by transfer to top storage and removal from top storage by draft or other augmented discharge.

Dynamically, top storage is free to gain or lose rapidly as a net result of excesses or deficiencies of rainfall, of draft, and of other kinds of transfer. But top storage variations are damped by the demands of transfer to or from bottom storage as equilibrium is disturbed. The large volume ratio between bottom storage and top storage, 40 to 1, or possibly more, gives the bottom storage great stability against rapid change and by the transfer effect limits the amplitude of variations in top storage.

In their 40:1 ratio between equivalent storage quantities, the bottom and top storage behave like a pair of reservoirs, one large and one small, connected by a pipe offering resistance to flow. Except for certain nearly steady leaks from the large reservoir, all changes are made through the small reservoir. Analogy with such reservoirs is imperfect since the movable boundary of bottom storage in the rocks is not a water–air boundary but a fresh-water–salt-water boundary in rock. Movement can be achieved only by also moving salt water extending out to the ocean bottom. The free surface in this direction is the surface of the ocean. The great area of the ocean, the resistance to flow in rock from the transition surface out to the sea bottom, and the 40 to 1 volume ratio of bottom storage give great stability to the transition surface.

As a result, sudden or abrupt changes in input or outgo, even when applied to bottom storage water as in a well drilled far below sea level, will be shown first by changes in the water table. In turn, the top storage is at any time a cumulation of plus or minus effects and a leading element with which bottom storage tends to seek equilibrium. When bottom storage is nearly in balance, the water table may vary between positions above and below that of equilibrium with the transition surface. Bottom storage and the position of the transition surface fluctuate with movement of water from or to top storage but in an amplitude far less than required for new equilibrium.

If bottom storage, in a lagging response to large past changes of the water table, is out of balance in one direction, the fluctuations of the water table will not lead to reversal of movement of the transition surface but only to changes in its rate of movement.

It is evident that if the unit transfer rate of flow per foot of unbalance between top and bottom storage is great, balance will be achieved quickly. An unbalanced condition could not then be great in amount or of long duration, otherwise amounts of water moved would exceed those for which we can account, and their movement would tend to hold the amplitude of water-table movement below values we observe. If the unit transfer rate per foot is negligibly small the Ghyben-Herzberg principle would be inoperative.

In order to explore the possibilities of the bottom storage theory, it is simpler to consider definite amounts of water. This will be useful despite our lack of exact or direct knowledge in some respects. Figures used below refer to the Honolulu system, Areas 1 to 4. Some of them are fairly well-established quantities based on measurement. Others represent amounts considered most consistent with the indirect knowledge we have and under the qualifications mentioned.

The total average rainfall in the Honolulu mountain intake area is about 129 million gallons daily. The amount taken by artificial draft with heads kept constant (a value we cannot directly measure) and with average or normal rainfall, is approximately 35 million gallons daily, including both public and private wells. This figure is supported by statistical analysis of draft, head, and rainfall data for the period 1926 to 1940. The amount which reaches the upper basal water body from both rainfall and possible transfer from bottom storage is not directly known but must lie between these two extremes and will here be discussed as 80 million gallons. (Various equations set forth in another part of this report indicate an amount above, rather than below, 80 mgd.)

Artificial draft for short periods may be as low as 20 or as high as 70 mgd, and it is believed that infiltration for short periods may be as little as 50 or as much as 120 mgd. By combining somewhat less than opposite extremes we conclude that against the average steady condition where infiltration equals draft plus leakage, the net residues may vary from about 30 mgd excess to 30 mgd deficiency. These seem to be about the largest differences that we know of; any supposition in regard to a movement of the diffusion zone at a more rapid rate will require support by an explanation of where such large quantities can come from or go to.

There are several estimates of the unit volume of top storage per foot of water-table change in the head range from 20 to 30 feet. They vary from 200 to 400 million gallons per foot for Areas 1 to 4, combined. For discussion we will take the round number of 300 million gallons. Rates of change of head for short periods approach but do not exceed 0.10 foot per day, either rise or fall. Such a change corresponds on the above storage rate to 30 mgd excess or deficiency. The coincidence is accidental; but the essential fact is that differences in supply of 30 million gallons are sufficient to achieve the indicated daily rate of increase or decrease of 1/10 times 300 million gallons.

But the probable unit amount of bottom storage corresponding to a sustained 1 foot of head difference at the water table is of the order of 40 times 300 million gallons or 12,000 million gallons, and for 0.10 foot it is 1,200 million gallons. Whether this figure is valid or is double or half the true figure is immaterial. The variation of +30 mgd to −30 mgd is wholly inadequate to make such changes in bottom storage. The lag, even without reference to friction, would have to be many days or months.

If there were no friction, so that 40/41 of all variations were at once transmitted to bottom storage, the daily rise or fall of the water table due to excess or deficiency of 30 mgd would necessarily be restricted to 2 or 3 thousandths of a foot.

The conclusion is indicated that fluctuations in the water table, and hence in the amount of top storage, of the magnitude observed are only possible because the interchange of water between top and bottom storage is impeded by all the rock lying between the two boundary surfaces. This occurs to a degree that permits the temporary application of the amounts of daily fluctuation mainly to the top storage and delays dissipation of these amounts to the enormously larger bottom storage change demanded by ultimate equilibrium. To summarize this brief exposition of the doctrine of bottom storage, the following corollaries are set forth:

1. The ratio of depth below sea level to height above sea level in the Ghyben-Herzberg system approximates 40:1. The ratio of corresponding storage amounts of water at the bottom and at the top in a balanced system is probably 40:1, or greater.
2. The amounts of water involved in daily fluctuations of the difference between draft and infiltration are of closely similar order of magnitude to the amounts of storage at the water table corresponding to observed extreme daily rates of change of basal head. Assuming the ratio indicated above, these amounts are wholly inadequate to effect the corresponding changes of storage at the zone of transition on any assumption of immediate or prompt transfer of water between top and bottom storage.
3. Each fluctuation of the water table and of top storage, away from equilibrium under the Ghyben-Herzberg theory, tends to be canceled, either by reversal at the water table through movement from or to bottom storage, or by corresponding change in bottom storage through similar movement. If the new position of the water table is maintained by persistent application of excesses or deficiencies, the balancing will eventually be accomplished by completed change at bottom storage; if the change at the top is not maintained, the equilibrium will be much more quickly restored by almost immediate reversal at the top, since the latter restoration only requires approximately 1/40 the amount of water and time that the former would require.
4. In the sense of movement, the top storage is the independent element, and the bottom storage follows with lag; in the sense of static inertia, the bottom storage is independent and the top storage tends to swing back to equilibrium with it except as it is held above or below by persistent excesses or deficiencies.

5. The rate of interchange of water between top and bottom storage is presumably proportional to the first power of the amount of unbalance which exists between them; its absolute rate is not yet known. To assume that it is very rapid is to postulate the movement of greater amounts of water than we can account for in any plausible way; to assume the rate too low is to nullify the Ghyben-Herzberg principle below the validity indicated by common observations.
6. If the lagging response of bottom storage operates, whatever the rate of response is, there is here a definite challenge to the supposition earlier made that when the head returns to a former value, the total storage in the system has returned to the same value. In view of the 40:1 ratio, it is evident that even if a considerable part of the response of bottom storage is achieved, the non-completed part may still be several times as great as the whole amount of change in top storage. Hence, it would vitiate any such postulate as that earlier made in regard to the basal head as a direct index of total storage.
7. Consideration of the amounts of water involved make it difficult to see how the shift of the transition zone by the 40 feet corresponding to a 1-foot change in basal head can be achieved short of many months, if not years. Moreover, the rise of the transition zone and shrinkage of bottom storage by the 600 feet corresponding to 15 feet loss of head since 1880, on the data we have, is presumed to have yielded something of the order 600 times 300 million gallons (180,000 million gallons) of water to draft and artificial leakage over and above the normal net amount from rainfall. If this entire shrinkage has been completed in the past 60 years (about 20,000 days) it has approximated 9 mgd of draft from bottom storage over the period. If it has not been completed, the average amount will have been less, but there may still be a fraction of present draft from that source. These are conservative figures; twice these amounts are more plausible than any lesser amounts. Whether the balancing of bottom storage is rather rapid, with only a few months lag and large amounts of water yielded into the daily inventory from storage, or whether the lag is much greater and over many years, the accounting for the water involved in the shifting of the transition zone and its effect on estimates of safe yield, or justifiable draft, remains a problem of the greatest importance in the future operation of the Honolulu water supply.

HYDROLOGIC DATA AND QUANTITIES

GENERAL

The basic question which led to the studies reported herein is that of "How much water can be taken from the ground and how and where can it be withdrawn?" Unfortunately, while it is believed that a great deal has been learned about the water supply and its behavior, this knowledge inhibits, rather than promotes, a direct, single, quantitative answer. So far as possible, because such estimates are simple and tangible, tentative figures will be offered for various quantities, but it must be emphasized that in most cases they will tend to mean more to the reader than to the writer, and they must be used with the realization that only with an elaborate set of definitions can they be regarded as reliable. In some instances magnitudes will be presented in graphic form which, in showing the interrelationship with other factors, will provide some of the necessary definition of conditions.

RAINFALL

The most reliable statement of rainfall for the Honolulu and Pearl Harbor areas is that contained in the isohyetal maps for the two areas (figs. 16 and 17). The detailed configuration of the isohyetal lines is subject to local modification when the data from needed rainfall stations are in hand, but the over-all quantities are probably within 10 or 12 per cent of the true value and are more precise than any other single quantity except the actual draft output as measured by pump stations.

Total rainfall quantities and net rainfall on areas believed tributary to basal water are given in tables 24 and 25.

Tables 24 and 25 give for various large units the amounts of rainfall based on rain-gage readings, on isohyetal maps, and on the classification of numbered hydrologic provinces from 1 to 139, inclusive. The outlines of the areas are shown in figures 16 and 17; the detailed measurements are tabulated in the file reports (Wentworth, 1938–1945: Kalihi, pp. 62–69; Manoa–Makiki, pp. 75–81; Pearl Harbor, p. 84). The figures given are based on average rainfall, as far as it has been determined. It is possible that the period on which the measurements are based may be one of abnormal rainfall; the error in the average quantities due to this cause is probably less than 5 per cent. The coverage by rain gages is not as satisfactory as it might be; given 25 to 50 years of record taken on a pattern of gages selected without restriction as to access and based on what we now know, it is possible that quantities for some local areas might be modified by 25 per cent, but this writer believes the over-all average quantities shown above are correct within 10 or 12 per cent.

Because of the proximity of the intake area to the areas of utilization of water, there is a very acute interest in the fluctuations in rainfall quantities in the Honolulu and Pearl Harbor areas. The effects of rainfall excess or deficiency are rather quickly shown by changes in head, and the latter are rightly interpreted as calling for some concern where they are of uncommon intensity or duration. No method has yet given valid predictions of deviations of rainfall from normal for periods a month or more in the future, though the subject has been investigated rather intensively during the 3 or 4 years just past by the sugar and pineapple industries (Leopold and Stidd, 1949). The best that can be offered is a probability analysis such as that summed up in figure 18 and on page 62. This chart is based on about 60 years of records which were not entirely complete or general in the earlier years. From the chart an estimate can be made as to the percentage rainfall excess or deficiency

TABLE 24

ESTIMATED WATER QUANTITIES BY ARTESIAN AREAS FOR HONOLULU (MGD)

HYDROLOGIC COMPONENTS*	MOANALUA AREA NO. 4	KALIHI AREA NO. 3	BERETANIA AREA NO. 2	MOILIILI AREA NO. 1	WAIALAE AREA NO. 5	HONOLULU TOTAL WAILUPE BARRIER TO HALAWA BARRIER
Mountain Intake Area (sq. mi.)	7.73	4.82	4.82	2.99	5.23	25.60
Total Rainfall	83.61	40.21	54.62	23.91	24.22	226.57
Rainfall on Caprock and Other Non-Tributary Areas	33.69	17.77	28.50	9.65	7.97	97.58
Mountain Rainfall	49.92	22.44	26.12	14.26	16.25	128.99
Estimated Runoff	6.20	6.75	6.40	4.30	2.94	26.59
Evaporation	9.99	4.48	5.22	2.85	3.25	25.79
Transpiration	11.07	6.89	6.88	4.27	7.47	36.58
Infiltration Remainder or Basal Intake	22.66	4.32	7.62	2.84	2.59	40.03

* In mgd except as otherwise indicated.

NOTE: For more detailed statement of methods by which these values have been reached, see accompanying discussion and the following two reports: Wentworth, 1938–1945, Manoa-Makiki, pp. 75–81; and Kalihi, pp. 62–69.

TABLE 25

ESTIMATED WATER QUANTITIES BY PORTIONS OF AREA 6, PEARL HARBOR (MGD)*

HYDROLOGIC COMPONENTS†	SOUTH HALAWA BARRIER TO WEST LIMIT WAIMALU DRAINAGE	WAIMANO AND WAIAWA	WAIAWA TO WEST KOOLAU MARGIN	TOTAL AREA 6
Mountain Intake Area (sq. mi.)	11.53	16.88	15.33	43.74
Facet and Apron Area (sq. mi.)	6.05	10.55	22.96	39.56
Total Rainfall (mgd)	105.05	149.18	165.86	420.09
Rainfall on Caprock and Other Non-Tributary Areas (mgd)	8.15	8.72	34.33	51.20
Rainfall on Facet and Apron Area (mgd)	19.85	23.81	38.88	82.54
Mountain Intake Rainfall (mgd)	77.05	116 65	92.65	286.35
Total Mountain Plus Facet-Apron Rainfall (mgd)	96.90	140.46	131.53	368.89

* For detailed areas and rainfall of hydrologic provinces 100 to 139, see Table 1, opposite page 84, Pearl Harbor report (Wentworth, 1938–1945).

† Development of estimates for runoff, evaporation, transpiration, and an infiltration remainder, as a part of this table, comparable to those items for the Honolulu area is not feasible. See discussion elsewhere in this report.

which is as likely as not to obtain for a period of given duration once in a given span of years. From such percentage figures quantitative estimates can be made and a concept developed as to the probable effect on basal heads, encroachment of salt, and the like, under assumed conditions of demand. Such a chart has only a moderate reliability and many years more record will be required to produce what could be called an accurate probability pattern. However, the present chart, being based on a systematic procedure and on all the data available, is much more reliable and more flexibly applicable that any isolated specific instances alone. Checks on probable variability for local stations or other areas can be used in conjunction with this chart to develop estimated variation data where more complete analyses are not available.

EVAPORATION AND TRANSPIRATION

No estimate of average evaporation or transpiration rates has been made with validity sufficient to be of value as a factor in estimating ground-water supplies. This was set forth by Hoyt many years ago (1934). Measurements made at two stations and reported by Stearns and Vaksvik (1935, pp. 202–213) and Stearns (1940, pp. 147–157) give a range of values and were in relation to conditions such that they cannot confidently be applied to any large intake area in calculating water quantities. The rugged terrane and diversified forest vegetation make the determination of these factors in sufficient precision for application to estimating over-all water losses inordinately difficult. In the interest of public understanding and of the determination of policies in forest management, a well-planned study by a trained specialist with adequate help and equipment would be justified. In the sense of estimating of annual safe yield in any particular area, this line of study is not considered likely to yield results of useful validity. Until such a study is made, no useful purpose can be served by listing categorical rates of evaporation and transpiration even though such rates may well be within the truth for some or much of the forest area.

RUNOFF

Runoff data can be used in two ways. One is as a component in the hydrologic equation, to be subtracted from the rainfall total for a given area, in estimating the infiltration residue. The other is simply as a measurement of an amount of discharge at a given stream gage. Runoff can be measured with more precision than evaporation or transpiration; however, the amounts shown by any feasible number of stream gages must fall somewhat short of the true runoff for the total area since there are various facet and other areas without definable stream channels. The estimation of how much runoff takes place from such areas during wet seasons is difficult and results in a considerable error in the total assumed runoff. Unfortunately, the hydrologic equation must stand as a whole; since the evaporation and transpiration are regarded as not estimable at present, the somewhat more valid estimate of runoff is of use only in setting outside limits for infiltration.

Within the areas discussed in this report, the chief interest in runoff measurements is in relation to recharge projects. There are fairly adequate measurements of runoff for the chief streams of the Honolulu area and these have been summarized in table 26.

TABLE 26

DISCHARGE IN MGD PER SQUARE MILE OF DRAINAGE AREA, HONOLULU STREAMS

NAME OF BASIN	ELEVATION OF GAGE	AREA OF BASIN	MEAN DISCHARGE	UNIT DISCHARGE
	feet	*sq. mi.*	*mgd*	*mgd/sq. mi.*
Waiomao	373	1.0	1.33	1.33
Pukele	345	1.2	1.47	1.23
East Manoa	294	1.0	3.02	3.02
West Manoa	291	1.1	2.84	2.58
Nuuanu	632	3.4	5.80	1.70
Kalihi	464	2.7	5.20	1.93
Moanalua	339	3.2	2.65	0.83

The total discharge averages about 22 mgd. The data show a rather large and not wholly explained difference from valley to valley in mean discharge per square mile of drainage basin. The measurements of discharge have been taken as the basis for plans for recharge projects which have been estimated to contribute about 6.8 mgd to the present basal water supply. These projects were deferred because of the war. It is hoped that they can be taken up in the near future.

There is an entirely inadequate pattern of gages on natural streams in the Pearl Harbor drainage area. There is some gaging of ditches at diversion points and a fairly complete measurement of flow from the Pearl Harbor Springs, but no close estimate of the total natural discharge across the 200-foot or comparable contour is practicable. Any application of a rate per square mile would be open to great uncertainty because of the great variation in the rates shown in table 26 for streams of the Honolulu area. Under the existing pattern of land use, diversion of streams to recharge ground water in the Pearl Harbor area is not indicated.

INFILTRATION

We should not pretend that we can offer a close estimate of the amount of rain water that enters the ground in the mountain intake portions of either the Honolulu area or the Pearl Harbor area. The mountain rainfall quantities for these two areas are 129 and 369 mgd, respectively. Each of these quantities is probably correct within 10 or 12 per cent of the total. The water which enters the ground and the water derived from decreases in storage, particularly bottom storage, must together equal the amount taken out by artificial means plus the amount reaching the ocean by inaccessible channels through natural leakage. Because, under our present concept, the water derived from bottom storage in the Honolulu area can be a large amount of water (possibly of the order of 5 to 10 mgd), which is not directly measurable, and because the amount of natural or ocean leakage is probably a still larger amount, also not measurable directly, and because these are on opposite sides of the equation, categorical estimates are impossible. Let us illustrate. Referring to the Honolulu area and using figures that are only assumptions:

$$\text{INFILTRATION} + \text{STORAGE CHANGE} = \text{DRAFT} + \text{OCEAN LEAKAGE}$$
$$70 + 10 = 40 + 40$$

This equation balances but has meaning only if we have fairly valid data. As long as means are lacking for measuring the amount of ocean leakage and also of storage change, we cannot in this way determine the amount of the infiltration. Elsewhere in this report it has been set forth that the infiltration cannot be estimated closely by the method of subtracting evaporation, transpiration, and runoff from total rainfall. Even if this were possible, it would still be impracticable to estimate safe yield because of the fact that storage change (at present) is probably additive to and ocean leakage subtractive from the infiltration before we get the safe yield. It does not appear that any consideration was given to ocean leakage or storage change by any of those making estimates of safe yield heretofore. Yet we know that prior to the drilling of any wells there must have been a natural leakage amounting, over any period of years, to the whole amount of the infiltration and thus maintaining equilibrium. If such leakage is regarded as leakage over the top of a barrier, the remainder being tight, we could consider the leakage as brought down to zero as soon as the head in any given basin is lowered below the outlet. Likewise, if we regarded the basal water as being held within a container with a tight bottom, we could say there is no effect of change of storage except at the water table, which is small. Previous estimates of safe yield, in making no allowance for change of storage or for continued leakage, have amounted to an acceptance of a model in which the only leakage was overflow leakage at the maximum head and in which the bottom of the assumed container was tight.

Such a concept is now quite unthinkable; we have abundant qualitative evidence that as long as the head of the basal water remains above sea level, the difference of head will induce movement through various openings toward the ocean as well as toward or from adjacent partially separated basins according to which head is the higher. We also have much evidence that salt water is rising and displacing fresh water at the bottom of the Ghyben-Herzberg lens. We have no escape from the qualitative conclusion that the basal water body is in hydraulic contact with the ocean and that it must expand or shrink in a lagging response to the change of head which its free water table shows.

Given these facts we must assume that artificial draft can take only that fraction of infiltration which is not lost by ocean leakage plus the amount which can temporarily come from shrinkage of the lens, particularly at the bottom. At the beginning of the well-drilling period, an increasing amount of artificial draft was made available by virtue of the decreasing leakage due to reduction of head. This process has continued, subject to the seasonal fluctuations of rainfall and head, to the point where the lowered head and rising salt zone have eliminated some of the deeper wells as sources of fresh water. The process can go farther with the result of making more water available by saving of leakage but not very rapidly because of the saline invasion of more wells and the consequent threat to private rights.

On the other hand, the water available from bottom storage, due to shrinkage of the bottom of the lens, can only be supplied once; if during and following a period of lowering much water is supplied from this source, the amount will progressively become less during subsequent sustained low heads. Continuing low heads may be required to equal demand, but the amount obtainable under steady conditions will probbaly fall off.

MOST PROBABLE VALUES

It has been pointed out why, under our present understanding of the hydrologic mechanism, the amounts of infiltration, or of leakage, or of yield from storage cannot be derived by simple addition or subtraction or direct measurement. The multiple correlations reported in another section represent our most reliable and promising approach to this problem known today. Derivation of equations under the least squares principle affords an opportunity to determine, not a fixed value for some given hydrologic quantity but, with the data at hand, the most probable way in which this quantity varies in relation to some other quantity and its most probable actual value for some assumed value of the other quantity. The method can be no better than the data available. It appears that during the period 1926 to 1940, on the assumption that the annual yield from shrinking bottom storage is a constant and that the yield from and loss to top storage cancelled out at a nearly equal head, the best relation of yield to rainfall and head is shown by the equation:

$$D = 98.6 + 3.39 \, f(R) - 2.39 \, H$$

The values of $f(R)$ in this equation represent a moderately successful adjustment of the rainfall data to explain the variation of draft but should not be regarded as final nor as applicable to any period other than 1926–1940, except as interpreted through the equation with caution.

The first interpretation we can make is that the variations of actual draft are best explained by using the $f(R)$ and H terms; that is, the rainfall variations and the leakage loss, to modify an initial total of about 100 mgd (a number of the better equations center around 90 to 100 mgd). This value in a physical sense was the amount daily available, hence infiltration plus any gain due to shrinkage in bottom storage, from which the ocean leakage due to the head was subtracted and up or down from which the differences due to high or low rainfall were felt.

The second interpretation is that the natural leakage (to the ocean or by any other route which depends on head) is best approximated by values of about 2.5 mgd per foot of head. This means that the natural leakage during that period, with heads from 23 to 30 feet, appeared to range from 58 to 75 mgd. Using these figures alone one would say that subtraction of the higher value from 100 mgd would leave an amount smaller than the known draft. However, during such a period of high head the rainfall is also high.

The third interpretation is more complex in that the value of f(R) is less readily tangible than the head. It must suffice to say that during the year 1939, for example, f(R) was plus 1.38 and during 1926 was minus 1.57, giving excess and deficiency during those years of 4.68 and 5.32 mgd, respectively. The difference was about 10 mgd. For short periods during those years the differences were still greater.

The question will be asked how it happens that during the last 7 or 8 years there have been years when the draft went above 60 mgd. The most immediate answer is that during that period there were such sustained demands and the conditions of head and draft were sufficiently modified that the 1926–1940 equation is not adequate. Among possible changes is the addition of the Red Hill shaft and the probable modification of the shape of bottom storage in response to the abnormally lowered heads; but we should recognize that sustained conditions of this sort are out of the range for most of the 1926–1940 period.

A new equation for the period 1940 to 1955, when data are available, will give a clearer evaluation of the source of the draft measured.

In the Pearl Harbor area, from an average rainfall in the intake area computed as 369 mgd, there is taken well over 200 mgd. The total measured in 1944 was 254 mgd, the sources of which are indicated in table 27.

The characteristics of the Pearl Harbor basal water supply are less well known than those of the Honolulu area, and insufficient work has been done by the method of multiple correlation to justify a firm conclusion. As in the Honolulu area, the draft is sufficient to lower heads rather rapidly when rainfall conditions are unfavorable, and it is not clear that significant amounts of additional water can be taken without having a detrimental effect on existing stations through lowering the heads and increasing the salinity in critical places. The draft of as much as 250 mgd from an area not known to receive more than about 369 mgd represents a remarkably large percentage and is probably to be explained in part by yield from shrinking storage. If this be the case, yield in the future under the same conditions of rainfall and head will be materially less.

THE PROBLEM OF SAFE YIELD

GENERAL

Any statement of the amount of water that can wisely be taken from the basal water supply systems of

TABLE 27

Total Known Basal Ground-Water Discharge (mgd) in Pearl Harbor Area (No. 6) (Koolau Water)

Type of Opening	U. S. Navy	Suburban Water, City and County	Board of Water Supply	Honolulu Plantation Co.	Hawaiian Electric Co.	Oahu Sugar Co.	Ewa Plantation Co.	Other*	Unused Water	Total
Artesian Wells	7.70†			27.91		42.18	51.26	2.25	?	131.30
Basal Shafts, Tunnels, Wells	10.00	0.61	6.68‖	1.43	10.9‡	3.99	21.2			54.81
Large Springs				1.4	25.5	7.5			33.7	68.10
Totals	17.70§	0.61	6.68	30.74¶	36.4¶	53.67**	72.46**	2.25	33.7††	254.21

* No measurements available; this estimate is based on an assumed average of 0.05 mgd for each of 45 wells.
† This amount will be much greater in future, owing to taking over of wells late in 1944.
‡ This amount is tunnel and well water, but is added to spring total at Hawaiian Electric Co. pool.
§ To this amount from Area 6, must be added about 19.3 mgd from Red Hill and certain other smaller amounts to get Navy over-all total in Honolulu–Pearl Harbor region.
‖ This is rate for period September to December, 1944.
¶ Hawaiian Electric Co. pumped 11.0 mgd of its total 36.4 mgd to Honolulu Plantation Co. for irrigation. Thus of total 37.4 mgd collected by Hawaiian Electric Co., 36.4 mgd is used once for condensers and 11.0 of this is used again for irrigation.
** Both these plantations develop some water from Waianae rock, Area 11, not included here.
†† This amount consists of excess discharge to the ocean from various of the Pearl Harbor spring groups. Prior to its discharge it has contributed to local wet-garden irrigation in unmeasured amounts.

Honolulu and Pearl Harbor involves not only the complexities and unknowns of hydrologic behavior but also the equally complex formulation of what can be called safe. The level of availability which can be considered the minimum of safety depends on the types of usage and the habits of the community. There is a large difference between agricultural and municipal use in this regard. There are times when total use in the Pearl Harbor agricultural area is no more than 15 or 20 per cent of the maximum. In the municipal unit of Honolulu, in ordinary times, the minimum use may be as little as two-thirds the maximum. In the municipal unit, water is a daily necessity for human life and community safety and the amount required cannot probably, in peace time or under any ordinary regime, be markedly curtailed below the level to which people have become accustomed. That it would be feasible technically and in a more disciplined society does not enter the picture at present.

Similarly, quality is somewhat relative; for agricultural use, water containing up to 500 ppm of chloride involves no particular problem, except that in dilution with more saline water either before application to plants or alternately it is not as effective as water of lower salinity. But for domestic purposes the present standard of the U. S. Public Health Service of 250 ppm cannot in practice be exceeded, and a chloride content of more than 150 ppm at any particular point in the Honolulu distribution system leads at this time (1950) to complaints by some persons. Since the natural composition of the main part of the Honolulu basal supply is chiefly around 50 ppm, it is open to question whether it would be possible, on lowering head and increasing the salinity to 100 or 150 ppm, to stabilize the composition at such a new level. If this is true—that pegging the salinity at a new level would be difficult not only because of the difficulty of controlling head but also because of departing from the steady condition which has in geologic time produced class II water—an additional reason is brought forward for caution in drastic lowering of head.

It seems to the writer inevitable that under pressure of regional and social patterns over periods of years there will be changes in the tolerable limit of amounts of salt and hardness in water as well as in the amount below which per capita usage cannot be held. It would be unrealistic not to recognize that 100 years from now the community will surely be using water in more prudent quantities per capita and will have grown to accept higher salt and hardness content, probably still well within existing limits of medical or industrial tolerance.

Municipal domestic use per capita will depend largely on the pattern of housing which is attained in the future. The American level of water usage and water-impelled sanitation is the highest in the world; no one would advocate lowering it, but over some generations the pattern on Oahu for the stabilized population may require an adjustment to the amount of water available.

We return to the definition of safe yield, which is the same as that of safe usage. In systems such as that of the Honolulu and Pearl Harbor area, the unsafeness of excessive draft may fall not on the contemporary population but on those living in the community at some future time. This is to say that an unwise increase in amount of water taken may not produce an immediate shortage of water or impairment of quality, but may initiate changes which, if continued, will be destructive to future water supply and may not be susceptible of repair by any action that can practically be taken in the future.

Opinions may differ as to how far we should operate for the present only and let the future take care of itself. However, we can be reasonably certain that in many ways the natural resources of the community, even if not being destructively depleted, are coming to be more and more difficult and expensive to produce. It does not appear wise to so use a given essential resource in one generation that the conditions of use are severely and destructively modified. We must recognize, however, that in response to slow changes in social and economic patterns methods of production and use may be so changed that conditions which today would be prohibitive will in the future be routine. The ultimate question of whether the status to which the water supply has come in some future time is destructive or prohibitive must be measured against the then-obtaining standard of use and method of exploitation.

We may now define safe (= socially justifiable) yield or usage as the rate of draft which under present conditions of use and exploitation is judged by competent opinion to be neither destructive to any contemporary exploitation by presently reasonable method nor trending irrevocably toward conditions which would deny to a future generation a like choice of reasonable method and level of exploitation and use. This is essentially a definition of the right of one generation. Adherence to this standard is particularly significant in the case of a renewable resource such as ground water. It is evident that each generation can equitably take such ground water as accumulates annually within its time. It happens that in order to do so there must be some reduction in volume of the amount held in storage. Some loss of storage is a condition of withdrawal by any method we now possess. While utilizing the existing condition of storage and necessarily modifying it, we probably in equity lack the right to so reduce the storage that continued use in the future, by the same or other methods, is jeopardized.

The foregoing principle means that safe usage does not imply a categorical amount of water, but rather a calculated estimate as to quantities of water, fluctuations of head, and changes in salinity which do not violate the aim set forth. In making such an estimate the most important criterion is head, the measure of accumulation at the top of the Ghyben-Herzberg lens. Consideration must be given to the effect of draft quantities on head and to the effect of both draft and head on salinity. Recognition must be given to the fact that methods of draft are being improved by the change from deep wells to skimming tunnels, but that not all users have made that change. It is a matter for negotiation, or possibly regulation, to determine how long a technically less defensible method can be maintained as reasonable. It is perhaps no more defensible for a well owner to expect conditions required by his obsolete type of draft to be maintained than for the operator of a large tunnel station to systematically so reduce the head as to destroy those conditions. To a large extent changes in method of exploitation take place through the operation of economic causes; the establishment of a water control commission to evaluate ground-water supplies and set up patterns for adjudication of rights has been advocated but the proposal has not been put into effect.

With increasing demand the lowering of heads during periods of reduced rainfall cannot under any existing control be avoided. Such head lowering in some places, such as most of the Pearl Harbor area, produces increases in salinity; in others, such as the four main areas of Honolulu, there is some increase in salinity in deeper wells near the coast but the main municipal draft from the Kaimuki, Beretania, and Kalihi stations and the Kalihi shaft has not so far changed composition. There is every reason to suppose that at some future time head lowering will bring increased salinity at the first three of these stations. This will probably come as the proximate result of seasonally lowered heads, but the ultimate cause may well be the result of lagging rise of the diffusion zone. This is imminent so long as the main city draft comes from the deep artesian wells, though we cannot predict the time at which it will take place. Plans have already been made for replacing each of the three artesian-well stations; the completion of these new stations should be accomplished at the earliest practicable date. The recent swing to rainfall higher than average, together with the slight flattening of draft trends since the end of the war, may give respite of so much as a decade before the head commences a downward tread; this is just enough, but no more than enough, to complete at least two of these stations.

Within this time, draft from private wells which are in danger of becoming salted may have sufficiently declined so that damage from lowered head will be much restricted. Lowering of head by sustained draft will increase the draft capacity by an amount which we estimate now at nearly 2.5 mgd per foot of lowering of head. Stearns advocated a purposeful lowering of head as a means of drawing more water and mentioned heads as low as 8 feet above sea level (Stearns and Vaksvik, 1935, pp. 456). This proposal has been opposed on the ground that the induced salting of artesian wells and other changes would be a wholly unjustified invasion of private rights. The present writer believes that progressive lowering of the heads in both the Pearl Harbor and Honolulu areas will take place in coming decades and that there will be a benefit from that decreased head through reduced natural leakage; but he does not feel that it should be advocated as a means of securing increased supplies. Moreover, there is reason to suppose that increased saline encroachment will be felt long before any such figure as 8 feet is reached. As far as an estimate can be hazarded, it is thought that physical conditions will set a limit to head lowering at a median value of perhaps 12 or 13 feet, with allowance for extreme dry season lowering to possibly 9 feet, at 50 to 100 years in the future. Such a level of operation would contribute substantial amounts of additional water, but some or all of this would only offset the amounts that are now coming from shrinkage of stored water. The ultimate production of water derived from annual rainfall, from the basal water system of the Honolulu area, allowing for 5 mgd additional from recharged water, may, under rigorously controlled conditions of lowered heads, reach a sustained level of as much as 70 mgd, 100 or more years in the future. It is not thought that all the necessary conditions of control will be achieved any sooner than this, and it is believed that during the next 50 years there will be periods of low rainfall when, under existing conditions, even a sustained 60 mgd will bring more destructive saline encroachment than came in the mid-forties.

For any immediate application, adherence to a standard of salinity not to exceed 70 ppm of chloride and not to exceed 80 ppm of hardness would be very attractive. These values include the chief stations of the municipal system of Honolulu, and to date the quality of water at these stations has been remarkably stable. Mention has been made elsewhere that such stability is attributed to the very large mass of water contained in the Ghyben-Herzberg lens of the Honolulu area, such that its quality has not yet responded to the changed equilibrium indicated by lowering the head from 42 to an average of perhaps 25 feet. The water of this mass is somewhat more saline than the various known high-level waters, and such water, carried in and slowly passing through such large lens segments, has been called class II water. We do not yet know whether its quality would deteriorate after some hundreds of years at the present heads but this has not yet taken place.

We must expect, assuming that heads will go still lower during future operations, that both salinity and hardness will increase. Though the layman is more generally aware of changes in salinity near the tolerance limit, it appears that in a municipal supply increases in the hardness might in certain industrial uses be in reality a more serious detriment than those in salinity. On the other side is the fact that for agricultural use salinity is the critical factor, and there is now a considerable amount of water produced in the Pearl Harbor area of which the salinity is not far from the usable limit. Here salinity is critical and hardness is not.

Building of basal skimming tunnels to replace deep wells will permit draft of more water and greater lowering of head without immediate local threat of prohibitive increase of salinity. However, because of this improved capacity these stations are likely to lead to more continuous and unrestrained head lowering and are certain to be the instrument of widespread modification of flow patterns within the Ghyben-Herzberg lens. Such head lowering and change of flow patterns at some future time will certainly result in increase in salinity and hardness through admixture of larger proportions of sea water. Up to the present time, at least in the Honolulu area, the water quality has been dominated and stabilized by the steady condition of the great mass of water in the Ghyben-Herzberg lens. Local wells, especially near the coast or where the drawdown is too great, have felt increase in salinity through overdraft, but this fact has not led us to believe that the main circulation in the lens has been modified. When such modification does take place through head lowering, it is reasonable to suppose that there may ensue a long period of readjustment of water quality in the direction of greater salinity, and it is thought that once such a change commences it is likely to be at least several decades before any new point of stability would be reached even if some new limit of head lowering could be adhered to.

It is well known that salinity up to three or four times that current in the bulk of the Honolulu water supply is experienced in some communities without clearly indicated adverse effect on health, and hardness much higher than that in the Honolulu supply is tolerated elsewhere. Granting that for sufficient reason considerable increases in both salinity and hardness some decades hence could and likely will be tolerated, the present writer is somewhat concerned over the difficulty of pegging the acceptable values of salinity or hardness at any new points, once the existing position is lost. The difficulty will be both human in the sense of psychology, economics, and administration and physical in that the inertia of a very large volume of water is involved, with attendant difficulty of estimation of probable end points. This seems much more serious than the simple acceptance of change in standards.

ELEMENTS OF A SOUND OPERATING PROGRAM

The operation of a water supply mechanism such as is represented by the Ghyben-Herzberg lens is in many ways comparable to the operation of a very large piece of machinery—in particular, a large piece of machinery with many of its parts hidden. To operate such a mechanism it is essential to proceed with much caution, having regard at each step for the possibility of reversing any contemporary trend.

The primary aims of such a program can be stated as follows:

1. Make no change in the natural condition of the ground-water system unless it will be a permanent improvement in the total of quantity with only a tolerable loss in quality of water produced, both for the present and for the future. Temporary addition to water quantities at the expense of availability, quality, or costs in the future is not justifiable.
2. Assume that the major water resource for Honolulu is the basal water lens, that large high-level water supplies are unlikely ever to be found, and that if any are found they will not alter the main reliance on the basal supply.
3. Assume that reliance chiefly on the water intake area near Honolulu is a well-founded policy and that draft of water from areas remote from the urbanized area should not be developed more rapidly than growth of the urbanized area itself, with the transition of land use from agriculture to urban settlement.
4. Assume that annual fluctuations of basal water level with increased human use, will probably be greater than they were under natural conditions and make calculated allowance for such increased fluctuations.
5. Move toward the construction and interconnection of water supply stations in the Honolulu and Pearl Harbor areas having a total emergency capacity of two to three times the steady regional yield capacity and at such spacing that any daily drawdown at one is only very mildly detectable at another. Such a condition in the Honolulu area will be approximately accomplished by the completion of the proposed Waahila, Papakolea, and Kapalama basal stations and the reconstruction of the Waialae station. It is nearly reached in the Pearl Harbor area from Aiea eastward except that the tunnel design in the Honolulu Plantation shaft and the Navy Halawa station are probably imperfect with reference to head lowering and avoidance of local, operational salt encroachment. Other stations, such as the Navy Waiawa station now being constructed, are indicated in the western part of the Pearl Harbor area.
6. With such stations in operation and with distribution mains sufficient to permit some flexibility of draft, it appears at present most effective to so pump the several isopiestic areas as to maintain approximately the existing relative heads except insofar as it is shown that ground-water storage in one area is more effective than in another. In advance of specific analyses to this end it can be assumed that the existing and past head relations are an indication of relative storage efficiency.

RECOMMENDED CONSTRUCTION AND RESEARCH PROJECTS

CONSTRUCTION

The following recommendations represent procedures which at this time (1951) are regarded by the writer as most likely to safeguard and assure long-term usefulness of the water supply of the Honolulu area, with more general and less specific reference to the Pearl Harbor area. Many of these projects have been discussed in the earlier manuscript reports, but not all the projects there discussed and recommended are recommended here. Some of the projects considered feasible in relation to the individual parts of the Honolulu area are, in a comprehensive view, at this time considered marginal or not on a parity with the major proposals endorsed here.

1. *Basal Tunnel Stations at Waahila, Papakolea, and Kapalama*

   To carry through a program of completing these three major stations and accomplish a calculated retirement of the corresponding artesian-well stations in the Moiliili, Beretania, and Kalihi isopiestic areas within the next 15 years is regarded as the most important single water supply objective that can be named. Early construction of at least one station is urged. The condition of rainfall and head has recently (1949) been very favorable, but is less so at present (1951). Even though we cannot predict years when marked lowering of head will again be felt, no one doubts that such lowering of head with progressively increased prospect of serious increase in salinity in some areas will be felt, quite likely before 1960. For several reasons, including specific needs of the distribution system, the order of construction should follow that in the above heading.

2. *Recharge Tunnels in Palolo, Manoa, Nuuanu, and Kalihi Valleys*

   Next to the essential basal tunnel stations, construction of the proposed recharge tunnels in the four chief valleys is considered most urgent in providing permanently efficient use of the water resources in the Honolulu area. There is less experience in such construction than in that of the basal skimming tunnels and it is desirable to construct the first of these tunnels at as early a date as possible so that a practical test will be provided which may suggest modification in the design of subsequent projects. There is exceedingly little experience on water recharging in formations comparable to those of Hawaii and most of the "water-spreading" on the mainland is quite irrelevant. Best guide to local requirements comes from the skimming tunnels themselves. The writer believes the danger from clogging is very small and can be dealt with by simple precautions. The real criterion of success of such tunnels is in the percentage of the water put down that we succeed in recovering.

3. *High-Level Tunneling*

   No further tunneling at high levels in Koolau rock (such as at Palolo Tunnel, or at west side of Pukele Valley, etc.) is recommended under conditions likely to prevail in the future.

4. *Valley Bottom Tunnels*

   As a fundamental contribution to the general water supply, the driving of shallow tunnels in Pauoa Valley or Nuuanu Valley is considered by the writer inadvisable. General conclusions on such projects have been set forth elsewhere. It is recognized that in reference to local gravity-water demands, development of any one of such projects might be justified, but the decision on such grounds lies outside the present report.

5. *Deep, Valley-Bottom Development in Nuuanu*

   A deeper exploration of the perched water bodies in Nuuanu Valley with reference to delivery either to the surface or to recharge the basal water body has been discussed (Wentworth, 1938–1945, Nuuanu–Pauoa, pp. 211–213). If this project is undertaken it should be treated as an over-all addition to the water supply and not as a development restricted to gravity delivery at a specified elevation.

6. *Pearl Harbor Spring Repair*

   In the Pearl Harbor area, apart from the addition of one or more basal tunnels such as the Navy Waiawa tunnel now under construction, the outstanding opportunity is in devising and carrying through a combined repair and development, first of one and eventually of all, of the Pearl Harbor Springs. Suggestions along this line have been made in the Pearl Harbor manuscript report. It is important to emphasize that the Pearl Harbor Springs represent large leaks from the Ghyben-Herzberg lens, without which the water would stand at a higher level. One form of conservation is to use as much as possible of this water, which is leaking naturally, in ways that serve to reduce other types of draft. This is worth while in the same sense that it would be worth while to convey water from a leaking tap to a garden patch needing irrigation. But it is not a justifiable ultimate procedure because the

> water continues to waste when not needed and is not held in storage during such periods. Using water from a leaky tap, where possible, is better conservation than putting in a new service line to serve a simple need for water; but it is not so good as repairing the tap so it does not leak and using therefrom just the water needed and no more.

At present not more than half the water issuing from the several Pearl Harbor Springs is used at all; moreover most of it issues with higher salinity than necessary and has, after discharge, poorer sanitary quality than it has while still in the basal water lens. The amount of water lost and impaired in quality is more than the community can afford to lose in view of the periodic, critical need for water. Control of the leakage represented by these springs would be an important step in a planned treatment of the Oahu water supply problem and would result in the availability of larger amounts of better water and in far better storage protection against dry season shortages. As stated above, the use of spring water after its escape is a secondary use which belongs only in a laissez faire pattern of water usage, and is inconsistent with the planned water development represented by construction of the modern type of basal water station.

The plan proposed by the writer is one of combined repair of the spring leakage and development of a comparable amount or more water by basal tunnel. The hydrologic conditions are not fully known, but it is believed they can be determined by a program of combined exploration drilling, water measurement, and progressive construction of cut-off structures and water-development tunnels. The fact that the emergence of the large amount of water shown in various springs is narrowly restricted to a zone a few feet wide and 5 to 15 feet above sea level justifies confidence that cut-off structures will not require placement to prohibitive depths below sea level. The tentative plan suggests use of successive sections of tunnel or ditch in bedrock between sea level and 25 feet above, first excavated and then sealed by concrete on the seaward face, leaving the landward face for intake purposes. These would be dug in sections of a length permitting partial dewatering and could be joined to form a continuous combined barrier and ring tunnel from which water could be drawn.

Two conditions must be met before such a project can be carried out. One is the assumption by some agency—federal, territorial, municipal, or corporate—of the operational expense of a job whose benefit would be regionwide and perhaps not immediately competitive with a simple water-producing tunnel. The other is the combining of exploration and hydrologic analysis with the successive units of construction so that continuous redesign and test could be made to secure the desired result. The ultimate objective would be to so repair and inactivate a given spring that the head of its area would be raised above the previously prevailing position relative to adjacent areas and concurrently and subsequently to expand a draft tunnel to the degree that a total draft in excess of the former spring flow and of superior quality could be drawn with a lowering of the water table to a lesser degree than induced by the free flow from the former spring.

It is believed that ultimately such a conservation procedure will come to be recognized as a community necessity; its development within the next quarter century would add greatly to available quantity and quality of water and, particularly, would expedite growth of our understanding of the hydrologic potentialities of the region. It should be understood that the writer intends no preference or advocacy for any particular method; if full-scale experiment shows that some plan of grouting is more effective than pouring mass concrete against one wall of a trench, then that procedure should be used. Emphasis is here given to the belief that a method can be found and that the above-mentioned aim can and should be achieved.

RECOMMENDED RESEARCH PROGRAM

The research projects mentioned below are the most important elements of a program of study which must continue to unfold, with increasing understanding and development of new methods. The present report summarizes progress in understanding to date; it includes what may be the most complete general geologic field survey that will be undertaken. However, it is only an introduction to the systematic analysis of the hydrologic behavior of the water supply system of southern Oahu. This analysis, in the writer's view, should be continued for a long time into the future.

1. *General Hydrologic Studies*

> At a certain stage of development of water resources, like other mineral resources, the location and kinds of projects are determined by need plus common knowledge or accidental discovery. At a later stage, when a systematic general understanding of geologic conditions has been developed, projects are formulated and carried through by specific application of such principles and local surveys by engineers and geologists. Still later, there comes a time when there is less emphasis on discovery, either accidental or by specialized studies, and when the critical evaluation of the probable entirety of resources and their regulated use and conservation become the foremost consideration. It is unnecessary to deny that some new discoveries will be made in order to recognize that in the Honolulu and Pearl Harbor area the preponderance of that water supply with which we have to work is already in sight, if not in hand, and that the continued, routine pursuit of measurement and formulation of its characteristics by the most competent specialists obtainable is essential to the most effective use and preservation of this vital supply.
>
> The word "routine" was used above because it is clear that no decade will furnish answers to queries about the water supply system that will be final or hold for all future time. Research as a basis for more efficient exploitation, processing, or use is routine for any major industry or utility.

The natural water supply of Honolulu is subject to fluctuations of climate as well as demand; its responses to increasing demand and its lagging behavior are made complex through an enormous storage volume. Its behavior in one decade will not repeat that in another, and the calculation of what quantities of water may be expected is not one to be accomplished by simple repetition. The development of the best understanding of the water supply mechanism in each period, as with the expanding of distribution system, the financial and other policies, is a problem for continued attack by the most competent research hydrologist available. The categorical completion at any one time of studies of this sort, with answers ready for use anytime in the future, cannot be expected any more than in the case of operational and financial problems.

2. *Analysis of Saline Encroachment*

Probably the most immediate and tangible of unit studies that might be listed under (1) above is that of making a complete, statistical study of all available data, plus some taken especially for the purpose, on the encroachment of salt in artesian wells of the Honolulu and Pearl Harbor areas. No one has been able to carry this study to a point that might be attained by the use of existing information, and, except for a few wells that have been given a somewhat systematic preliminary attention, the large body of data on salinity is raw, unadjusted, and only in a desultory way tied up with contemporary heads, discharges, and other conditions of the basal water circulation.

The chief objective of such a study is to determine the true or average surface of transition from fresh water to salt water and to measure the rate of rise of that surface in response to past and present lowering of the basal head. Three sources of information are possible. The first of these consists of the various measurements of salinity of artesian-well water under ordinary conditions with little or no control of head or draft conditions, as in the past, but with more complete mathematical treatment. The second is the testing of various wells under controlled conditions, with sampling from various depths and the installation and use of test pipes in sealed artesian wells. The third is the installation of a complete diffusion-zone test well, with multiple sampling pipes so arranged as to give a complete profile from salt to fresh water through the whole zone of transition.

3. *Diffusion-Zone Test Well*

For the ultimate determination of the position of the surface of transition and the making of an adequate estimate of rates of change of bottom storage the installation of multiple-tube, transition-zone test wells is believed to be the most promising procedure. One such installation is now being made at Well 101, Richards Street and Ala Moana, and much valuable experience gained as to methods. The general procedure has been set forth in manuscript reports. Guided by results from the installation and testing at Well 101, it is urged that pipes be placed in suitably located wells that are being sealed and that multiple sampling pipes be placed in those wells selected as most likely to supply the crucial information required. This information as to position and rate of rise of the zone of transition in each of the several areas has a controlling bearing on the program of replacement of artesian-well stations by basal tunnel stations in the Honolulu area.

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MAP of HONOLULU and VICINITY

To Accompany The Geology and Ground-Water Resources of the Honolulu–Pearl Harbor Area, Oahu by Chester K. Wentworth

Based chiefly on U.S.G.S. maps

BOARD of WATER SUPPLY
HONOLULU
1951